Maastricht University

“A Co-operation of Observers”

Citation for published version (APA):

Beiermann, L. (2023). “A Co-operation of Observers”: Crafting knowledge infrastructures for microscopy. [Doctoral Thesis, Maastricht University]. Maastricht University. https://doi.org/10.26481/dis.20230215lb

Document status and date:
Published: 01/01/2023

DOI:
10.26481/dis.20230215lb

Document Version:
Publisher's PDF, also known as Version of record

Please check the document version of this publication:

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“A Co-operation of Observers”

Crafting Knowledge Infrastructures for Microscopy

Lea Beiermann

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An early version of Chapter Two has been accepted for publication as Beiermann, Lea. "Reproducing Rotifers: 'Working Images' and the Making of a Microscopy Community in the Nineteenth Century." *Transactions of the American Philosophical Society* 111, no. 4 (in press).

Chapter Three reworks Beiermann, Lea. "'A Method for Safe Transmission': The Microscope Slides of the American Postal Microscopical Club." *The British Journal for the History of Science* 54, no. 4 (2021): 403-422.

“A Co-operation of Observers”

Crafting Knowledge Infrastructures for Microscopy

DISSERTATION

to obtain the degree of Doctor at Maastricht University,
on the authority of the Rector Magnificus, Prof. dr. Pamela Habibović

in accordance with the decision of the Board of Deans,
to be defended in public
on Wednesday, 15 February 2023 at 13:00 hrs by

LEA BEIERMANN

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Dr. Geoff Belknap (National Museums Scotland)
Prof. Dr. Omar Nasim (Universität Regensburg)
Prof. dr. Emilie Sitzia

This research was funded by a PhD in the Humanities Grant of the Dutch Research Council (Nederlandse Organisatie voor Wetenschappelijk Onderzoek), grant number PGW.18.033/6344.

Contents

Acknowledgments

> At their best, acknowledgments dismantle the myth of the lone, self-contained genius-at-work, and instead expose the messy interplay of institutional support, finances, intellectual genealogies, and interpersonal chaos that shape how an idea is brought into the world.[1]

They say it takes a village to complete a PhD, and it took several to finish mine. I will defend this dissertation in Maastricht. However, due to the complexities of grant writing, I started my PhD at the University of Cologne, where I had only just begun to build an academic community when I moved back to Maastricht. One and a half years into the PhD, at the start of the Covid-19 pandemic, I had to build myself another, digital village online. When the heavy rain of July 2021 flooded my parents' basement, the thought that this was just a taste of future, more severe climate catastrophes kept me from writing my dissertation. But neighbours, friends and family all came together to help, and I continued to write. During my time in Cambridge in early 2022, I found not only intellectual sparring partners in the PhDs at Cambridge HPS but also compassionate fellow humans, as we watched, in horror, the Russian army invade Ukraine. A PhD is an intellectual challenge. However, in a world in crisis, it also takes emotional support and solidarity to complete a PhD, and I am grateful for all the kindness I received along the way.

The idea for this PhD was born during a research internship at the University of Leicester, where I got to know (and love) nineteenth-century history of science and technology. At Leicester I was welcomed by Gowan Dawson, Geoff Belknap, Richard Fallon and Matt Wale, who were all generous with their time and thoughts – I thank them for it. Back in Maastricht, I developed my ideas into an NWO grant application together with Raf De Bont and Cyrus Mody, who, after my stint at Cologne, became my PhD supervisors. Stefanie Gänger, my Cologne supervisor, continued to support me from a distance. Thank you all for your time and (generally excellent) ideas, your critical questions, and for sharing my enthusiasm for even the most obscure topics. I am a bit like the microscopists I researched: interested in almost anything, always dabbling in something new. Thanks for letting me be myself while helping me to stay on track. I couldn't have wished for a better team of PhD advisors. Thanks also to the members of my PhD assessment committee, who took the time to read this dissertation very carefully – I look forward to discussing it with you during the defence.

I am also indebted to my Maastricht colleagues. The FASoS research communication group – Joeri Bruyninckx, Eva Durlinger, Anna Harris, Sally Wyatt and Veerle Spronck – challenged me to think of new ways of communicating history of

[1] Emily Callaci, "On Acknowledgments," *The American Historical Review* 125, no. 1 (2020): 126-31.

science and technology. I learned a lot from all of you – thank you. I also thank Amrapali Zaveri and Susan Schreibman for their early feedback on my citizen science project, Jacob Ward and Vincent Lagendijk for their teaching support, sharing of ideas and papers, occasional career advice, and digital trivia nights during lockdown, Alexandra Supper for her thoughtful comments on one of one of my chapter drafts, as well as Geert Somsen for his trust in my abilities as a reviewer. I shared my office with many colleagues over the years and enjoyed the chats and coffee breaks with all of them, but my office mates Marith Dieker, Jorijn van Duijn and Claudia Egher made me feel welcome at the beginning of my PhD and less worried about the years ahead, and that's a lot. Thanks. I always found much support among the FASoS PhDs – thanks to Mayra Murkens, Denise Petzold, Mareike Smolka, Veerle Spronck (again), and many others for their help along the way. Mayra – thanks for being there through thick and thin, from desperate last-minute teaching prep sessions to celebrating our successes together.

I also got to meet and learn from many people outside Maastricht. Thanks to the archivists who shared their ample knowledge of microscopy and history of technology with me, especially Sara Schechner, Lee Macdonald and Wolfgang Wimmer. Thanks to Richard John and Laura Newman for their generous reading of early paper drafts. Nick Hopwood provided valuable feedback on a paper during my time in Cambridge, while Daniel Belteki showed me the city and was happy to discuss the wildest ideas for possible careers in history of science and STS – many thanks. My WTMC cohort was a wonderful group of smart and supportive fellow PhDs and a constant source of inspiration – thank you all. During the first Covid-19 lockdown, I found a digital history of science community in the members of the BSHS and was glad to organise events and write a paper together with them. Thank you. Moreover, a large part of my research into microscopy illustrations wouldn't have been possible without the many participants of my citizen science project, and especially Peter Mason, who became a real ally in organising *Worlds of Wonder* and analysing the crowdsourced data. I can't thank you enough, Peter. I am also very grateful to the Historians for Future members, especially Elizabeth Hameeteman, Isabelle Schürch, Elliot Honeybun-Arnolda, Gustave Lester, Emily Pawley, Sam Grinsell, Richard Staley, Hillary Briffa and Mathijs Boom. Thanks for your support and solidarity, and for making the future look a little brighter.

Tobias – thanks for reading and commenting on this dissertation, and for eight years of walking and talking together every now and then. Thanks also to my new colleagues at ada for cheering me on to get this PhD done. Christina, Coco and Sarah – thanks for sticking with me and having my back, always. My parents, the best imaginable, equally supported me when I wanted to become an inventor, a detective, a physicist, a microbiologist, an archaeologist, and a writer. Perhaps as a historian of technology, I am now a bit of everything – thank you. Simon – thanks for being my first co-conspirator, for your fight for social justice and optimism-despite-everything. You are an inspiration. Nicolai – on our hiking trips you always make me climb (or pull me up?) the highest mountains. Maybe the PhD was our highest yet. Thanks for everything.

Duisburg, 10 December 2022

1 Introduction: Crafting Knowledge Infrastructures for Microscopy

On entering the shop of James W. Queen & Co. at 924 Chestnut Street, Philadelphia, a customer in need of a microscope may have felt overwhelmed by their choices. Founded in 1853, James W. Queen & Co., retailer and manufacturer of scientific instruments of all kinds, stocked simple microscopes (little more than magnifying glasses), compound microscopes, including monocular and binocular instruments, and microscope accessories made by American, English, French and German manufacturers. Customers could choose among watchmaker's glasses, simple flower microscopes, linen provers ("for counting the threads in linen fabrics"), school and student microscopes, dissecting microscopes, portable travelling microscopes, family microscopes and clinical microscopes.[1] The instrument of the customer's choice could then be fitted with additional devices ranging from turntables for making specimen slides to dissecting troughs, which allowed microscopists to dissect delicate specimens under water, and polarising prisms for mineralogical analyses.

In 1888, the *Scientific American* praised James W. Queen & Co. as the "largest and most comprehensive [business] of its kind in the United States or the world."[2] The early 1880s had seen a steep growth in the number of American scientific instrument dealers, but the wide choice of microscopes available at James W. Queen & Co. was difficult to match.[3] The company's turnout of scientific instruments had "reached proportions which can hardly be appreciated without a visit to the shops."[4] Still, the *Scientific American* tried to recreate the experience by walking its readers through the various departments at James W. Queen & Co. Although the company was more of a microscope retailer than manufacturer, it had its own brass foundry, machinery for grinding lenses, and spacious, bright working rooms for its engineers. In addition to a comprehensive stock of instruments made by foreign and domestic manufacturers, James W. Queen & Co. offered a broad array of trade catalogues and magazines, some of them edited by company staff. The *Scientific American* reported that James W. Queen & Co. made "a specialty of

[1] J. W. Queen & Co., *Priced and Illustrated Catalogue of Optical Instruments, Made, Imported and Sold, Wholesale and Retail by James W. Queen & Co.* (Philadelphia: James W. Queen & Co., 1870), 26.
[2] "The Manufacture of Scientific Apparatus," *Scientific American* 58, no. 17 (1888): 258.
[3] For an overview of American microscope manufacturers, see Donald L. Padgitt, *A Short History of the Early American Microscopes* (London and Chicago: Microscope Publications Ltd., 1975).
[4] "The Manufacture of Scientific Apparatus," 258.

securing catalogues of all foreign makers of apparatus in different branches of science, and of keeping informed as to the scientific and practical knowledge and apparatus of the day," making the company a veritable "bureau of information."[5]

To guarantee a steady supply of microscopes and the latest microscopy news, James W. Queen & Co. relied on a dense network of trade and communication infrastructures, spurred by major shifts in communication and transport from the mid-nineteenth century onwards. Postal reforms in many European countries and the United States, such as the introduction of the British Uniform Penny Post in 1840, and the international parcel post from 1880 onwards, facilitated the exchange of scientific specimens and instruments.[6] The growing number of scientific instrument dealers in the late nineteenth century did not merely coincide with reforms of national and international postal services, but their businesses grew alongside the post, as home workshops became mail-order companies and microscope slide subscriptions a business model.[7] Moreover, from the 1860s onwards, transatlantic travel became more affordable, allowing for more regular crossings of the Atlantic to visit scientific congresses and trade fairs.[8] In addition to transatlantic shipments of instruments from European manufacturers, James W. Queen & Co. received a host of microscopy periodicals, most of them published by British and American microscopy societies.

Microscopy clubs and societies had begun to multiply in Great Britain in the 1860s, accompanied by a rise in richly illustrated microscopy journals and handbooks.[9] In the 1870s, the United States saw a similar surge in the number of mostly middle-class microscopy societies. These organisations were committed to advancing microscopy, mainly through regular publications, society meetings, exhibitions and other social events, but also by setting technical standards for microscopy. Their microscopy periodicals – some of them society transactions, some full-fledged scientific journals – were widely circulated. Often, these periodicals invited their readers to exchange observations, as well as microscope specimens,

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[5] "The Manufacture of Scientific Apparatus," 259.
[6] See Jean-François Fava-Verde, "Victorian Telegrams: The Early Development of the Telegraphic Despatch and Its Interplay with the Letter Post," *Notes and Records: The Royal Society Journal of the History of Science* 72, no. 3 (2018): 275-292; Richard R. John, *Spreading the News: The American Postal System from Franklin to Morse* (Cambridge, MA: Harvard University Press, 1998); Cornelius Neutsch, "Standardisierungen im Postverkehr zwischen 1815 und 1914," in *Standardisierung und Integration europäischer Verkehrsinfrastruktur in historischer Perspektive*, ed. Gerold Ambrosius et al. (Baden-Baden: Nomos Verlagsgesellschaft mbH & Co. KG, 2009), 59-80.
[7] See Erich Hintzsche, "Schweizer 'Mikroskopische Institute' aus der zweiten Hälfte des 19. Jahrhunderts," *Gesnerus* 26, no. 1-2 (1969): 73-116.
[8] See Mark Rennella and Whitney Walton, "Planned Serendipity: American Travelers and the Transatlantic Voyage in the Nineteenth and Twentieth Centuries," *Journal of Social History* 38, no. 2 (2004): 365-83.
[9] There was a general rise in scientific periodicals in Britain at the time, see Bernard Lightman, "Popularizers, Participation and the Transformations of Nineteenth-Century Publishing: From the 1860s to the 1880s," *Notes and Records: The Royal Society Journal of the History of Science* 70, no. 4 (2016): 343-359.

through their correspondence columns. In the 1870s and 1880s, the centre of microscope production gradually shifted from London to the German city of Jena, where the Zeiss company was located, but throughout the nineteenth century there were only few German societies or periodicals dedicated entirely to microscopy, in comparison to their American and British counterparts.

Microscopists relied on the burgeoning trade and communication infrastructures of the late nineteenth century not only to circulate scientific news, microscopes, and other technical equipment, but also to learn microscopy, a set of scientific skills that required a lot of practice. The wide variety of microscopes and accessories available at James W. Queen & Co., ranging from small flower microscopes to complex histological instruments, demonstrates that using a microscope – and choosing the right kind of instrument for the task at hand in the first place – could be challenging. The use (and manufacture) of a compound microscope and its many accessories, the preparation of microscope slides, as well as the observation of specimens, required a high level of practical skill, which could only be gained through innumerable hours of training and was often difficult to translate into written instructions. As the president of the British Postal Microscopical Society, J.W. Measures, declared in 1887, "the beginner is unable to learn from the books on the microscope all the minutiae of so fine an art as mounting [microscope specimens]."[10]

It has long been a tenet in the history of science and technology that the kind of skill, or craft knowledge, referred to by Measures can best be learned from others through personal interaction and on-site instruction. As the historian Myles Jackson explains in an article reviewing the scholarship on skill in the history of science, skills "are acquired through direct contact and personal observation of experimental technique."[11] Since skills require some "manual dexterity" and seem difficult, if not impossible, to codify in text, historians have so far tended to assume that learning skills from other scientific practitioners requires some form of embodied collaboration.[12] Historical research into skill has been oriented towards rather narrowly confined sites of knowledge exchange where practitioners directly meet and interact.[13] Consequently, while there has been much scholarly interest in the long-distance circulation of historical scientific knowledge and instruments over the past few decades, the sharing of scientific *skills* at a distance has received

[10] Henry Leslie Osborn, "Editorial – Postal Microscopical Clubs," *The American Monthly Microscopical Journal* 8, no. 2 (1887): 33.
[11] Myles W. Jackson, "Labor, Skills, and Practices in the Scientific Enterprise: Recent Works in the Cultural History of Science," *The Journal of Modern History* 71, no. 4 (1999): 902.
[12] Ibid.
[13] See, for example, Lissa Roberts, Simon Schaffer, and Peter Dear, eds., *The Mindful Hand: Inquiry and Invention from the Late Renaissance to Early Industrialisation* (Amsterdam: Edita KNAW, 2007). See also Thijs Hagendijk, "Learning a Craft from Books: Historical Re-enactment of Functional Reading in Gold- and Silversmithing," *Nuncius* 33, no. 2 (2018): 198-235.

much less attention.[14] Only recently have historians, mostly early modernists, begun to question the assumption that acquiring skills requires historical actors to be co-present, a discussion that this dissertation extends to the history of microscopy in the late nineteenth century.[15]

I argue that late-nineteenth-century microscopists developed ways of sharing even "practical knowledge," as the *Scientific American* called it, remotely. The question of how that was possible lies at the heart of this dissertation. It asks how microscopists who hardly ever met in person managed to pass on craft knowledge of microscopy, ranging from the making of observations and microscope preparations to the production of scientific instruments. I show that in order to learn microscopy at a distance, microscopists relied on trade and communication infrastructures that allowed for the sharing of skills. Skills may be difficult to translate into writing, but when we consider late-nineteenth-century infrastructures in all their diversity, drawing on a broad array of historical sources, we see that they made it possible to share not only texts but also images and objects, or replicate practical demonstrations in different places. This dissertation, therefore, challenges the common assumption that craft knowledge is primarily acquired from others on-site. At the same time, it invites us to explore the kinds of infrastructure that can help generate craft knowledge and reconsider the role of infrastructure in sharing scientific skills within a community of practitioners. Before elaborating on the concepts of skill and infrastructure underlying this dissertation, the following section first surveys the literature on the history of microscopy and outlines the scholarly contribution this dissertation seeks to make.

From the History of the Microscope to the History of Microscopy, and Back

In *The Microscope and the Eye*, the historian of science Jutta Schickore states that "the microscope has rarely been a favorite topic for historians," a view generally shared by the few scholars who have written about the history of microscopy.[16] Ann

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[14] Overall, there seems to be a paucity of work on nineteenth-century scientific craftsmanship in the historiography, at least in comparison to the research undertaken by early modern scholars. Early modernists tend to regard the personal, direct interaction among craftspeople as the primary way of knowledge exchange. See, for example, Pamela H. Smith, ed., *Entangled Itineraries: Materials, Practices, and Knowledges across Eurasia* (Pittsburgh, PA: University of Pittsburgh Press, 2019); Pamela H. Smith, "In a Sixteenth-Century Goldsmith's Workshop," in *The Mindful Hand: Inquiry and Invention from the Late Renaissance to Early Industrialisation*, ed. Lissa L. Roberts, Simon Schaffer, and Peter Dear (Amsterdam: Edita KNAW, 2007), 33-58; Chandra Mukerji, "Tacit Knowledge and Classical Technique in Seventeenth-Century France: Hydraulic Cement as a Living Practice among Masons and Military Engineers," *Technology and Culture* 47, no. 4 (2006): 713-733.

[15] See, for example, Heidi Hausse, "The Locksmith, the Surgeon, and the Mechanical Hand: Communicating Technical Knowledge in Early Modern Europe," *Technology and Culture* 60, no. 1 (2019): 34-64; Sven Dupré, "Doing It Wrong: The Translation of Artisanal Knowledge and the Codification of Error," in *The Structures of Practical Knowledge*, ed. Matteo Valleriani (Cham: Springer International Publishing, 2017), 167-88.

[16] Jutta Schickore, *The Microscope and the Eye: A History of Reflections, 1740-1870* (Chicago: University of Chicago Press, 2007), 15. This has also been argued in Ann F. La Berge, "The History of

La Berge, historian of medicine, offers several explanations for this neglect. For the better part of its history, the microscope was not only a scientific instrument but also an optical toy passed around for entertainment in bourgeois salons, possibly making the history of microscopy "not a lofty enough history for a historian of science."[17] Also, the microscope – unlike the telescope – was never linked to only one scientific discipline. Since the historiography of science was long organised around disciplines, the history of microscopy may have been a research topic unlikely to be picked up by historians of science. Well into the 1980s, the relevant literature mainly consisted of accounts written by antiquarians and museum curators, who painstakingly recorded the technological changes of the instrument over time, but rarely wrote histories of the technology in its scientific and social context.[18]

Since the 1990s, however, historians have taken a more contextualised approach to microscopy. Marian Fournier, Edward Ruestow and Catherine Wilson, in their respective work on seventeenth-century microscopy, have shown how European naturalists, spearheaded by Robert Hooke and Nehemiah Grew in England, Marcello Malpighi at Bologna, and Antoni van Leeuwenhoek and Jan Swammerdam in the Dutch Republic, became increasingly interested in the world of the small.[19] Ruestow portrays microscopy as a social as much as a technological endeavour, being intertwined with "cultural traditions, social relations, and personal sensibilities."[20] Fournier and Wilson take a more internalist approach, carefully delineating the philosophical assumptions underlying the research undertaken by the leading microscopists and natural philosophers of their time. Moreover, Ruestow and Fournier explain what they consider a decline of microscopy in the eighteenth century, arguing that macroscopic approaches to anatomy, including vascular injection, ultimately won out over microanatomy.

More recent work, however, refutes the view that microscopy was largely abandoned in the eighteenth century. Instead, Marc Ratcliff suggests that the eighteenth-century, although perhaps not a time of sensational discoveries in microscopy, was crucial for building scientific consensus and aligning the observations made by microscopists.[21] Like Ratcliff, Jutta Schickore contends that microscopy continued to thrive in the eighteenth century. She argues that microscopy

Science and the History of Microscopy," *Perspectives on Science* 7, no. 1 (1999): 111-142; Bernard Lightman, "The Microscopic World," *Victorian Review* 36, no. 2 (2010): 46-49.

[17] La Berge, "History of Microscopy," 120.

[18] See La Berge, "History of Microscopy." A notable exception is J. A. Bennett, "The Social History of the Microscope," *Journal of Microscopy* 155, no. 3 (1989): 267-280.

[19] See Marian Fournier, *The Fabric of Life: Microscopy in the Seventeenth Century* (Baltimore: Johns Hopkins University Press, 1996); Edward G. Ruestow, *The Microscope in the Dutch Republic: The Shaping of Discovery* (Cambridge, UK: Cambridge University Press, 1996); Catherine Wilson, *The Invisible World: Early Modern Philosophy and the Invention of the Microscope* (Princeton, NJ: Princeton University Press, 1995).

[20] Ruestow, *The Microscope in the Dutch Republic*, 5.

[21] See Marc J. Ratcliff, *The Quest for the Invisible: Microscopy in the Enlightenment* (Farnham: Ashgate Publishing, 2009).

became part of polite science, the scientific activities of wealthy ladies and gentlemen, which took place not only in the public but also, less visibly, in the domestic sphere. While the first half of Schickore's *The Microscope and the Eye* is dedicated to epistemological and methodological discussions relating to the trustworthiness of observations made with the microscope in eighteenth- and early-nineteenth-century Britain, the second half examines similar conversations among leading German anatomists and physiologists in the mid-nineteenth century.

If only few historians have studied microscopy up until the mid-nineteenth century, even fewer publications have looked at microscopy during the second half of the nineteenth century, maybe owing to historians' preoccupation with the epistemological questions that emerged at an earlier time when the use of the microscope and its reliability as a scientific instrument were contested.[22] Of course, as Lorraine Daston and Peter Galison have shown, the question of how to interpret what was seen through the microscope continued to spark controversy well into, and probably beyond, the twentieth century.[23] Microscopy as such, however, was certainly no longer considered a controversial scientific method by the end of the nineteenth century. By then, microscopy had become well integrated in university and school education, which, as Graeme Gooday and Stephen Jacyna argue, entailed some didactic challenges but ultimately strengthened the position of the microscope in the life sciences, as well as microscopists' interpretation of scientific phenomena.[24]

Overall, as La Berge so eloquently writes, there has been a turn away from "the history of microscopes to the history of microscopy" since the 1990s, as historians have come to adopt the view that technical considerations alone "can explain neither the rise, flourishing, and apparent decline of microscopy in the seventeenth and eighteenth centuries, nor its resurgence in the nineteenth century."[25]

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[22] Notable exceptions are Daniel Liu's dissertation, which looks at the use of the microscope in protoplasm research in the nineteenth and twentieth century, and, perhaps, Robert-Jan Wille's *Mannen van de microscoop*, which follows a group of Dutch lab biologists to the Dutch East Indies, but is more concerned with embryology than microscopy in particular. Robert-Jan Wille, *Mannen van de microscoop: de laboratoriumbiologie op veldtocht in Nederland en Indië, 1840-1910* (Nijmegen: Uitgeverij Vantilt, 2019); Daniel Liu, "Visions of Life and Matter: Protoplasm, Scientific Microscopy, and the Origins of Molecular Biology, 1839–1941" (PhD dissertation, University of Wisconsin-Madison, 2016).

[23] See Chapter Three in Lorraine Daston and Peter Galison, *Objectivity* (New York: Zone Books, 2007).

[24] See Graeme Gooday, "'Nature' in the Laboratory: Domestication and Discipline with the Microscope in Victorian Life Science," *The British Journal for the History of Science* 24, no. 3 (1991): 307-341; L. Stephen Jacyna, ""A Host of Experienced Microscopists": The Establishment of Histology in Nineteenth-Century Edinburgh," *Bulletin of the History of Medicine* 75, no. 2 (2001): 225-253.

[25] La Berge, "History of Microscopy," 138. See also Bennett, "The Social History of the Microscope." Note that there is another set of publications, often authored by literary scholars, looking at microscopy in fictional literature, theatre and music. Since this dissertation is not much concerned with microscopy in the arts, a thorough review of these works is beyond the scope of this introduction, but some examples are Francesca Brittan, "On Microscopic Hearing: Fairy Magic, Natural Science, and the 'Scherzo Fantastique'," *Journal of the American Musicological Society* 64, no. 3 (2011): 527-600; Martin Willis, *Vision, Science and Literature, 1870-1920: Ocular Horizons* (London: Pickering & Chatto, 2011). See also Meegan Kennedy's forthcoming book, *Beautiful Mechanism*.

In fact, today's historical accounts of nineteenth-century microscopy rarely focus on technical considerations. The instrument and its makers, as well as microscope slides and the tools used to record and distribute observations, do not feature prominently in the recent historiography.[26] Moreover, since the microscope became a mass-produced object in the late nineteenth century, it is important to acknowledge the commercial entanglements – the business history – of microscopy if we want to include the instrument and its makers in our research, which historians of nineteenth-century science have long tended to avoid. None of the few monographs on the subject, neither Jutta Schickore's work, nor the forthcoming books on microscopy by the literary scholar Meegan Kennedy, deal with nineteenth-century microscope makers, or the material aspect of making and sharing observations, and preparing microscope slides at the time.[27]

While this dissertation builds on the social histories of microscopy published from the 1990s onwards, it argues that if we want to answer the question of how skills were shared among microscopists, it is necessary to bring the microscope and microscopy tools back into the historiography of microscopy in the late nineteenth century. If we conceive of microscopy as the set of skills, or craft knowledge, that it was – the careful manipulation of instruments and recording of observations – then we need to consider the tools microscopists made and used. Pamela Smith, in developing "alternative taxonomies of knowledge-making," has characterised craft knowledge as collaborative, empirical, particularistic (adaptable to the particularities of local materials and environments) and open to public scrutiny.[28] Just like Jackson in his review of the historical literature on skill, Smith argues that craft knowledge is acquired through personal interaction and imitation, an argument that echoes Michael Polanyi's classic work on tacit knowledge, experiential knowledge that cannot be explicated.[29] Following this characterisation of craft knowledge, much recent work in the history of knowledge has focused on the local knowledge production among artisans. The downside to this, as James

[26] Historians associated with the AHRC-funded *Making Visible* project have studied the material aspects of early modern microscopy, see Sietske Fransen, "Antoni Van Leeuwenhoek, His Images and Draughtsmen," *Perspectives on Science* 27, no. 3 (2019): 485-544.
[27] However, microscope manufacturers do appear in more general histories of scientific instrument making in the nineteenth century, for example in Alison D. Morrison-Low, *Making Scientific Instruments in the Industrial Revolution* (Abingdon: Routledge, 2007); Alison D. Morrison-Low, Sara J. Schechner, and Paolo Brenni, *How Scientific Instruments Have Changed Hands* (Leiden: Brill, 2016). Moreover, a special issue edited by Ilana Löwy investigates the production and use of microscope slides in the twentieth and twenty-first centuries: Ilana Löwy, "Microscope Slides in the Life Sciences: Material, Epistemic and Symbolic Objects: Introduction," *History and Philosophy of the Life Sciences* 35, no. 3 (2013): 309-318.
[28] Smith, "In a Sixteenth-Century Goldsmith's Workshop," 35.
[29] See Michael Polanyi, *The Tacit Dimension*, repr. ed. (Gloucester, MA: Smith, 1983). Harry Collins provides a comprehensive overview, and classification, of concepts of tacit knowledge in the scholarly debates that followed Polanyi's work in *Tacit and Explicit Knowledge* (Chicago: University of Chicago Press, 2010).

Secord writes in his widely cited article on knowledge in transit, is that "[the] more local and specific knowledge becomes, the harder it is to see how it travels."[30]

Still, the last two decades have seen a growing literature on historical global networks of knowledge exchange. Unlike earlier macrolevel world histories, these more recent inquiries into global networks attempt to consider both "globally extensive circulation and locally intensive theatres of exchanges."[31] Miles Ogborn and Charles Withers refer to this approach as a new challenge of "working between and across . . . scales" by combining local, thick descriptions of scientific practices with analyses of larger communities, or globe-spanning networks.[32] In particular, object biographies have proven to be an effective way to "work across scales" and at the same time acknowledge how the material qualities of objects shape scientific practices. Historians of science taking a biographical approach reconstruct the lives of objects as they change and move between places, and examine the things, actors and practices that gather around them.[33] As Robert Kohler has argued, following the movement of scientific artefacts across national borders makes it possible to embed local case studies of practitioners using objects within a broader analysis of transnational scientific communication.[34]

And yet, little attention has been paid to the question of how scientific *skills* travel. This dissertation argues that to understand how microscopists acquired and shared their skills at a distance, we need to consider the role of infrastructure. As I will show, imparting craft knowledge of microscopy at a distance was intertwined with the skilful, and often tacit, use of various infrastructures. Historians of science have only quite recently begun to turn to the material logistics and infrastructures of knowledge exchange, despite their more longstanding interest in knowledge circulation.[35] This turn towards infrastructure asks us to acknowledge the skill it takes to build and maintain knowledge infrastructures, and to expand our range of actors in history of science to include builders of infrastructure, such as specimen dealers and other tradespeople, or even post officers.[36] The

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30 James Secord, "Knowledge in Transit," *Isis* 95, no. 4 (2004): 660.

31 Lissa Roberts, "Situating Science in Global History: Local Exchanges and Networks of Circulation," *Itinerario* 33, no. 1 (2009): 24.

32 Miles Ogborn and Charles W. J. Withers, eds., *Geographies of the Book* (Farnham: Ashgate, 2010), 19.

33 See, for example, Lorraine Daston, *Things That Talk: Object Lessons from Art and Science* (New York: Zone Books, 2007); Stefanie Gänger, *Relics of the Past: The Collecting and Study of Pre-Columbian Antiquities in Peru and Chile, 1837-1911* (Oxford: Oxford University Press, 2014); Cyrus C. M. Mody and Michael Lynch, "Test Objects and Other Epistemic Things: A History of a Nanoscale Object," *The British Journal for the History of Science* 43, no. 3 (2010): 423-458.

34 See Robert E. Kohler, "A Generalist's Vision," *Isis* 96, no. 2 (2005): 224-229.

35 Stefanie Gänger argued in 2017 that despite an increase in historical research into the circulation of knowledge, the term 'circulation' remained underdefined, and was even used to describe a unidirectional dissemination of knowledge. Stefanie Gänger, "Circulation: Reflections on Circularity, Entity, and Liquidity in the Language of Global History," *Journal of Global History* 12, no. 3 (2017): 303-318.

36 These more recent histories of knowledge circulation that take into account the affordances and constraints of material infrastructures include, for example, James Poskett, *Materials of the Mind: Phrenology, Race, and the Global History of Science, 1815-1920* (Chicago: University of Chicago Press,

notion of infrastructure that this dissertation draws on is elaborated in a later section of this chapter. In general terms, the dissertation broadly follows Susan Leigh Star and Karen Ruhleder's definition of infrastructure as a relational order enabling people, objects, work routines and organisations to function together.[37]

Star and Ruhleder also argue that "infrastructure both shapes and is shaped by the conventions of a community of practice."[38] In that sense, infrastructure is inextricably entwined with the community of users that forms around it – in this dissertation the community of microscopists that shaped, and was shaped by, the infrastructures that made it possible to share craft knowledge of microscopy in the late nineteenth century. Moreover, by assisting trained and untrained researchers in acquiring skills in microscopy, the infrastructures built and maintained by the microscopy community helped to provide an informal scientific education, and they also became entangled with the more formal scientific training offered by schools and universities. In addition to craft knowledge and infrastructure, the formation of scientific communities around shared infrastructure, and the provision of science education by and for the microscopy community are the third and fourth thematic threads that run through the chapters of this dissertation.

For the twentieth century, Cyrus Mody has shown that probe microscopists formed an "instrumental community," a "network of individuals who view their involvement with a particular type of instrument and/or instrumentality as ratifying their connection to other nodes in the network," with instrumentality being a "way of doing things" afforded by the instrument.[39] Late-nineteenth-century microscopists viewed themselves as connected by their use of the microscope, too. This dissertation further elaborates the notion of instrumental community by exploring how material infrastructures of making and doing microscopy affected microscopists' membership in their community. This means that the following chapters examine how certain infrastructures afforded or restricted access to the community, for example considering which kinds of illustrations could be duplicated through certain printing techniques, allowing only some microscopists to share their observations with the rest of the community. My historical analysis, therefore, is akin to the work of historians of science who have researched the materiality of media and how it shapes scientific communities, for instance James Mussell's work on the periodicity of the periodical press and how it came to be entwined with

2019); Anne Coote et al., "When Commerce, Science, and Leisure Collaborated: The Nineteenth-Century Global Trade Boom in Natural History Collections," *Journal of Global History* 12, no. 3 (2017): 319-339; Felix Driver, Mark Nesbitt, and Caroline Cornish, eds., *Mobile Museums: Collections in Circulation* (London: UCL Press, 2021).

[37] See Susan Leigh Star and Karen Ruhleder, "Steps toward an Ecology of Infrastructure: Design and Access for Large Information Spaces," *Information Systems Research* 7, no. 1 (1996): 111-134.

[38] Star and Ruhleder, "Steps toward an Ecology of Infrastructure."

[39] Cyrus C. M. Mody, *Instrumental Community: Probe Microscopy and the Path to Nanotechnology* (Cambridge, MA: MIT Press, 2011), 10.

the rhythm of scientific gatherings, or Jonathan Topham's study of the effect of "changing technologies and economics of illustration" on the audiences reached with scientific periodicals in the late eighteenth and early nineteenth centuries.[40]

Since this dissertation revolves around the question of how microscopists acquired microscopy skills at a distance, it employs a concept of community that does not necessarily regard community members as being co-located or interacting physically. It follows Patrick Leary's notion of a "virtual community," which he originally used to analyse community-building in and around periodicals in the nineteenth century.[41] Leary observes that periodicals which invited readers to contribute to their pages often produced lively correspondence columns and helped to establish virtual relationships among their readers, as well as rules for interaction. At the same time, editorial choices, including the layout of pages, the mixing of voices and genres, and the serialisation and distribution of periodicals, shaped the physical communities interacting with them.[42] While periodicals were only one of several communication mechanisms used by microscopists, all groups of microscopists discussed in the following chapters met virtually in some way, making Leary's notion of community particularly useful for my argument.

In addition to defining membership in their community, microscopists also used their knowledge infrastructures to provide education on microscopy and the natural sciences more broadly, within their community and beyond. The rise of microscopy societies, periodicals and scientific instrument dealers in the second half of the nineteenth century was directly linked to the restructuring of science education at schools and universities. Microscopes, accompanied by a rising number of textbooks on microscopy, became essential in training students to observe scientific phenomena, as part of a broader turn towards *Anschauungsunterricht*, or teaching through immediate visual perception.[43] Science professionalisers like the English scientist Thomas Huxley were keen to enlist the support of microscopy

[40] See Jonathan R. Topham, "Redrawing the Image of Science: Technologies of Illustration and the Audiences for Scientific Periodicals in Britain, 1790–1840," in *Science Periodicals in Nineteenth-Century Britain: Constructing Scientific Communities,* ed. Gowan Dawson et al. (Chicago and London: University of Chicago Press, 2020), 66; James Mussell, *Science, Time and Space in the Late Nineteenth-Century Periodical Press: Movable Types* (Aldershot: Ashgate, 2007). For a more general discussion of the rise of the scientific journal and its effect on the scientific community, see Alex Csiszar, *The Scientific Journal: Authorship and the Politics of Knowledge in the Nineteenth Century* (Chicago: University of Chicago Press, 2018).

[41] See Patrick Leary, "A Victorian Virtual Community," *Victorian Review* 25, no. 2 (2000): 61-79.

[42] For a close study of how nineteenth-century periodicals created their audience, see Lorna Huett, "Among the Unknown Public: Household Words, All the Year Round and the Mass-Market Weekly Periodical in the Mid-Nineteenth Century," in *The Lure of Illustration in the Nineteenth Century: Picture and Press*, eds. Laurel Brake and Marysa Demoor (Basingstoke: Palgrave Macmillan, 2009), 128-148.

[43] See Gooday, "'Nature' in the Laboratory;" Henning Schmidgen, "Pictures, Preparations, and Living Processes: The Production of Immediate Visual Perception (*Anschauung*) in Late-19th-Century Physiology," *Journal of the History of Biology* 37, no. 3 (2004): 477-513; Nancy Anderson and Michael R. Dietrich, eds., *The Educated Eye: Visual Culture and Pedagogy in the Life Sciences* (Hanover, NH: Dartmouth College Press, 2012).

societies in reforming education in the life sciences, while making clear that society members without formal scientific training could ultimately only play a marginal role in professional scientific research. Moreover, as the next chapter will show, commercial natural history dealers seized the opportunity provided by educational reforms to equip schools and universities with textbooks, scientific instruments, slides, as well as living microscope specimens and instructions on how to observe them.

Looking at how microscopists provided a scientific education is the fourth and final thread that runs through this dissertation. The four themes discussed – craft knowledge, infrastructure, community-building and science education – connect the chapters of the dissertation and will be drawn together in the conclusion to help answer the question of how microscopists acquired craft knowledge of microscopy. By focusing on those four themes, this dissertation demonstrates that it can be rewarding to move away from the epistemological discussions revolving around the establishment of truth claims that have so far dominated the literature on the history of microscopy. Conceiving of microscopy as a set of skills that involves the careful manipulation of instruments and specimens brings to the fore historical actors who have rarely been put in the limelight in the literature, including illustrators, as well as instrument and slide makers, who built and maintained the infrastructures of the microscopy community and helped to share craft knowledge of microscopy methods with a diverse community of learners.

Periodisation, Geographical Scope, and Sources

One of the main concerns in the history of microscopy scholarship since the 1990s has been to understand how users of the microscope, as well as the wider public, came to trust the instrument, and how microscopists achieved consensus on their observations.[44] As a result, much of the literature has focused on early modern microscopy or microscopy in the early nineteenth century, when the use of the microscope was controversial even among scientific practitioners. By the mid-nineteenth century, however, the development of achromatic and aplanatic objectives had remedied the most troublesome optical aberrations of microscope lenses, and the emergence of cell theory in the late 1830s had helped to increase scientific interest in microscopy.[45] In 1839, the first microscopy society was founded, the Microscopical Society of London, which would later become the Royal Microscopical Society (RMS).

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[44] Some publications that revolve around this question are Gooday, "'Nature' in the Laboratory;" Schickore, *The Microscope and the Eye*; Ann F. La Berge, "Debate as Scientific Practice in Nineteenth-Century Paris: The Controversy over the Microscope," *Perspectives on Science* 12, no. 4 (2004): 424-453.

[45] See Dieter Gerlach, *Geschichte der Mikroskopie* (Frankfurt a. M.: Harri Deutsch, 2009).

But it was only in the 1860s that microscopy societies and periodicals started to multiply in Britain and, around a decade later, in the United States. In both countries, postal microscopy societies, which availed themselves of growing railway networks and postal reforms, emerged in the 1870s. It was in the 1870s, too, that the German manufacturer Carl Zeiss began to draw on the calculations made by the physicist Ernst Abbe to mass-produce microscopes, which ultimately affected established trade infrastructures and cemented the shift of the centre of microscopy from Britain to the German Empire.[46] For all these reasons, the second half of the nineteenth century is a particularly interesting time for scholars who are keen to understand the formation of trade and communication infrastructures in the microscopy community, and how they made it possible for craft knowledge of microscopy to travel. The following chapter will consider some microscopy books and periodicals published in the 1850s and 1860s, but the bulk of this dissertation will focus on microscopy in the 1870s until the end of the century.

As the nineteenth century drew to its close, Charles Smiley, editor of the *American Monthly Microscopical Journal*, lamented the decreasing attendance at microscopy society meetings and the disappearance of local societies.[47] He was not the only one to mourn the declining interest in microscopy. Microscopy periodicals increasingly struggled to gain subscribers and most ceased publication.[48] Moreover, by 1900, the centre of microscope production had undeniably shifted to the German Empire. Whereas the 1880s had seen a rise in American microscope producers, only few of them managed to continue their business past the turn of the century.[49] In Britain, too, manufacturers struggled to keep up with the German microscope production, and many local societies disappeared or merged with more broadly positioned natural history societies.[50] Thus, by the turn of the century, the infrastructures that had shaped microscopy in the mid- and late nineteenth century were in decline or had been significantly transformed. This is the reason why this dissertation does not consider the history of microscopy after 1900.

Just like its temporal scope, the spatial scope of this dissertation is determined by late-nineteenth-century knowledge infrastructures and the groups of microscopists that formed around them. It was mainly in Britain and the United

[46] See Stuart M. Feffer, "Ernst Abbe, Carl Zeiss, and the Transformation of Microscopical Optics," in *Scientific Credibility and Technical Standards in 19th and Early 20th Century Germany and Britain*, ed. Jed Z. Buchwald (Dordrecht: Springer, 1996).
[47] See Charles W. Smiley, "Editorial," *American Monthly Microscopical Journal* 18 (1897): 259-263.
[48] See Smiley, "Editorial."
[49] See Padgitt, *A Short History of the Early American Microscopes*.
[50] William H. Brock, "Patronage and Publishing: Journals of Microscopy 1839-1989," *Journal of Microscopy* 155, no. 3 (1989): 249-266; Gerard L'E. Turner, *Essays on the History of the Microscope* (Oxford: Senecio Publishing Company, 1980).

States that microscopy societies were founded and a wealth of microscopy periodicals circulated.[51] In the German lands, too, microscopy handbooks proliferated from the mid-nineteenth century, yet microscopy societies and periodicals remained rare.[52] Microscopy was popular in the German lands, as evidenced by illustrated handbooks, or the microscopy demonstrations at Berlin's *Urania* science theatre, but the field was not formalised through societies or periodicals dedicated exclusively to connecting microscopists.[53] The same can be said about France, where medical microscopy had a long tradition and bacteriology flourished at the end of the nineteenth century, but microscopy was rarely formalised through periodicals and hardly recognised as a research domain of its own.[54] Therefore, Chapters Two and Three of this dissertation focus on Britain and the United States, before Chapter Four looks at how the German manufacturer Zeiss and his collaborator Ernst Abbe connected with British and American microscopists in order to collaboratively innovate Zeiss' microscopes.

In that respect, this dissertation differs from Schickore's *The Microscope and the Eye,* which regards the German lands as the centre of microscopy from the mid-nineteenth century onwards and does not return to British, or American, microscopy after mid-century. Looking at late-nineteenth-century microscopy from the perspective of infrastructure, this dissertation argues that we need to regard German microscopists as firmly embedded in the knowledge infrastructures built by their British and American contemporaries. This infrastructural perspective also has consequences for the types of sources that inform my historical research. Whereas most of the literature on nineteenth-century microscopy revolves around the most acclaimed scientists of their time and mainly draws on their published scientific texts, this dissertation shows that infrastructures in microscopy were not necessarily built by trained scientists and cannot be understood by looking at scientific publications only. In order to understand how craft knowledge of microscopy could be shared at a distance, we need to study more diverse sources, such as trade catalogues, low-brow scientific periodicals, notebooks, drawings, and scientific instruments.

Therefore, I draw on a wide range of physical and digital sources.[55] The physical collections that proved most valuable for my research were the two RMS collections at the Oxford History of Science Museum, the papers of the American

[51] See Lightman, "The Microscopic World;" Gerard L'E. Turner, *The Great Age of the Microscope: The Collection of the Royal Microscopical Society through 150 Years* (London: Taylor & Francis, 1989).
[52] See Andreas W. Daum, *Wissenschaftspopularisierung im 19. Jahrhundert* (Munich: R. Oldenbourg, 1998); Brock, "Patronage and Publishing."
[53] The public science displays at *Urania* are discussed in Kristin Becker, *Affe, Mond und Meer: Inszenierungen von Wissen und Wissenschaft im 19. und frühen 20. Jahrhundert* (Berlin: Kulturverlag Kadmos, 2014).
[54] The lack of long-running French microscopy periodicals is mentioned in Brock, "Patronage and Publishing."
[55] For an overview of the collections consulted, see Appendix A.

Postal Microscopical Club at the Academy of Natural Sciences, Philadelphia, and Ernst Abbe's correspondence with British microscopists held by the Zeiss company archives in Jena. The RMS collections mainly consist of unpublished material, such as minutes of meetings, cash books, subscription registers, notebooks and sketchbooks. The sketchbooks were especially useful in reconstructing how microscopists recorded their observations. The large collection of scientific instruments at the Oxford History of Science Museum also offered me an opportunity to become more familiar with nineteenth-century microscopes. The papers of the American Postal Microscopical Club, including transcripts of the notes circulated alongside microscope slides, allowed me to follow the production and postal exchange of slides, while Abbe's correspondence with the RMS Fellows made it possible to recognise their contribution to the production of microscopes at the Zeiss company. These unpublished physical sources were complemented with a wealth of digitised published material – German, British and American microscopy books and periodicals – available at the Biodiversity Heritage Library (BHL), the HathiTrust Digital Library and the Internet Archive. Taken together, the sources show how unpublished notes and sketches changed as they were published (and changed again when microscopists copied published illustrations by hand), and how microscopists collaborated through the correspondence columns of periodicals.

Moreover, as the next chapter will explain in more detail, illustrations of microscopes and microscope specimens, and reproductions of those illustrations, are central sources in this dissertation, as they helped me understand how microscopists learned to make observations with their instrument. In order to trace the movements of late-nineteenth-century microscopy illustrations as they were used and reproduced, and to reconstruct the network of people interacting with them, I launched a crowdsourcing project in April 2019, *Worlds of Wonder*. According to the digital humanist Mia Ridge, crowdsourcing means "taking work once performed within an organisation and outsourcing it to the general public through an open call for participants."[56] In online crowdsourcing projects, the work is most often broken down into a sequence of tasks that can be solved without much effort, like identifying, classifying, transcribing or tagging items. To distinguish between (often paid) crowdsourcing of any kind of microtasks and voluntary participation in research the latter is also termed "citizen science" or "participatory science."[57]

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[56] Mia Ridge, "Crowdsourcing Our Cultural Heritage: Introduction," in *Crowdsourcing Our Cultural Heritage*, ed. Mia Ridge (Ashgate: Aldershot, 2014), 1.

[57] Note that citizen science includes, but is not limited to, web-based crowdsourcing projects – citizen scientists partipate in research in various forms, in both digital and physical spaces. See Kelly Moore, "Powered by the People: Scientific Authority in Participatory Science," in *The New Political Sociology of Science: Institutions, Networks, and Power*, ed. Kelly Moore and Scott Frickel (Madison, WI: University of Wisconsin Press, 2006), 299-323; Ridge, "Crowdsourcing Our Cultural Heritage: Introduction."

The *Worlds of Wonder* project I developed for my PhD research invited citizen scientists to identify and classify illustrations in nineteenth-century microscopy publications and flag reproductions of illustrations. *Worlds of Wonder* ran from April 2019 to April 2020 and was hosted by the Zooniverse citizen science platform, which has accommodated some of the largest web-based citizen science projects over the last decade.[58] *Worlds of Wonder* attracted ca. 2,400 participants, who looked at nearly 20,000 pages and made some 63,000 classifications.[59] In the *Worlds of Wonder* classification workflow, citizen scientists were shown a page from a historical microscopy publication, asked if there was an illustration on the page and, if their answer was yes, to describe what they saw in the illustration. If the illustration was signed, they were also asked to transcribe the signature of the illustrator.[60] Each page was shown to at least five citizen scientists if the first few classifiers indicated that it included an illustration, or to at least three citizen scientists if the classifiers agreed that there was no illustration. After completing those tasks, the citizen scientists could choose to discuss the page they had classified – or any other topic broadly related to the project – in the *Worlds of Wonder* Talk forum.

The publications uploaded to *Worlds of Wonder* were hosted by the Biodiversity Heritage Library (BHL), whose staff have been involved in several crowdsourcing projects over the past couple of years.[61] The microscopy publications chosen included British, American and German periodicals, handbooks, textbooks and flyers. I selected publications that were dedicated to the use of microscopes and circulated widely, judging by contemporary book reviews, library catalogues, trade catalogues and present-day archival catalogues. I also included several short-lived publications, among them journals and books which received negative reviews.[62] My choice of publications was affected by the range of titles (and editions) available in the BHL, as well as the skills and preferences of the citizen scientists. For instance, there were fewer German publications available, and fewer citizen scientists who felt up to the task of classifying them.

Considering the compromises I made in my choice of publications, as well as the mistakes occasionally made in classifying images and transcribing illustrator names, the data gathered by *Worlds of Wonder* should not be treated as a collection of wholly accurate and representative data on microscopy illustrations in the

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[58] Joe Cox et al., "Defining and Measuring Success in Online Citizen Science: A Case Study of Zooniverse Projects," *Computing in Science & Engineering* 17, no. 4 (2015): 29.
[59] See https://www.zooniverse.org/projects/lbeiermann/worlds-of-wonder. Accessed on 11 August 2022. Since Zooniverse estimates the number of participants based on the IP-addresses used, this number may not be accurate if some citizen scientists used multiple devices.
[60] See Appendix C for an overview of the workflow.
[61] See G. Costantino and T. Rose-Sandler, "Crowdsourcing and BHL: Current Projects That Allow Users to Help Us Improve Our Library," *Biodiversity Heritage Library Blog*, 2014, https://blog.biodiversitylibrary.org/2014/11/crowdsourcing-and-bhl-current-projects-that-allow-users-to-help-us-improve-our-library.html. Accessed on 10 September 2022.
[62] See Appendix B for a complete list of publications analysed on *Worlds of Wonder*.

second half of the nineteenth century. However, the data can be used to trace the circulation of microscopy illustrations, and to lay bare some of the infrastructures used by late-nineteenth-century publishers, editors, illustrators, and printers. For example, I looked for recurring names of illustrators, microscope manufacturers and specimens to find out which (and whose) illustrations were (re)printed in which publications. I was also able to draw on the data collected by *Science Gossip*, a citizen science project launched by the ConSciCom research group on Zooniverse in 2015, which invited citizen scientists to classify illustrations in nineteenth-century natural history periodicals.[63] The data generated from three microscopy-related periodicals, *Hardwicke's Science Gossip*, the *Journal of the Royal Microscopical Society* and the *Journal of the Quekett Microscopical Club* were particularly useful for my analysis.

After aggregating and searching the crowdsourced data, I used the full-text search of the BHL, as well as the HathiTrust library and the Internet Archive, to gather information about the illustrators who appeared in the crowdsourced data, looking for mentions of their names. Some of these mentions were certainly lost due to the deficiencies of optical character recognition, but locating only a fraction of illustrators' names by manually perusing journals and society reports would have been a strenuous, if not impossible, task.[64] The digital data collected through *Worlds of Wonder*, *Science Gossip,* and the full-text search mainly informed Chapter Two, which, in following a set of microscopy illustrations and their makers, looks at how microscopists developed and shared observational skills. The chapter demonstrates how digital methods enable historians to write about historical characters who did not publish and of whom very little archival material is left.

Theoretical Framework: Infrastructural Inversions

In 1883, the *American Monthly Microscopical Journal* published a letter asking whether the journal's readers could "suggest the probable cause of the breakage of many [microscope] slides in the mails, and propose some method for their safe transmission, thus promoting a freer exchange of microscopical preparations among preparers, with a consequent increase and diffusion of microscopical knowledge."[65] The letter was signed by "M.A.B. Longmeadow, Mass.," which probably stood for Mary Ann Booth, a prolific maker of microscope preparations from

[63] The *Science Gossip* project is documented at https://conscicom.web.ox.ac.uk/. Accessed on 11 August 2022.
[64] For a discussion of the accuracy of OCR in digital collections, see Bob Nicholson, "The Digital Turn," *Media History* 19, no. 1 (2013): 59-73; David A. Smith and Ryan Cordell, "A Research Agenda for Historical and Multilingual Optical Character Recognition," *NUlab, Northeastern University* (2018), https://repository.library.northeastern.edu/downloads/neu:m043p093w?datastream_id=content. Accessed on 11 August 2022.
[65] Mary Ann Booth, "Breakage of Slides in the Mail," *American Monthly Microscopical Journal* 4, no. 2 (1883): 38.

Longmeadow, Massachusetts. Booth also wrote reports on the exchange of slides organised by the American Postal Microscopical Club for the *American Monthly Microscopical Journal*.[66] She reviewed the slides with an eye to the preparer's skill, and she judged the preparations by whether they would endure years of circulation and the rough treatment by postal workers. Notably, Booth's letter and reports show that a preparer's skill went beyond the preparation of microscope slides. It included knowledge of how to navigate the infrastructures used to exchange slides, which would materialise in weather-resistant cements for specimen mounting and sturdy packaging materials – as well as Booth's frequent use of pseudonyms in the gendered infrastructure of correspondence columns.[67]

Mary Ann Booth's letter to the editor is also interesting from an analytical perspective. It foregrounds the infrastructures that organised her knowledge exchange with other microscopists. Usually, as Susan Leigh Star and Geoffrey Bowker have observed, infrastructures are "arrangements that, by design and by habit, tend to fade into the woodwork."[68] Despite their crucial role in facilitating and shaping knowledge exchange, infrastructures remain in the background and are only rarely recognised by those familiar with them, at least as long as they function smoothly. In her letter, Booth addressed the infrastructures that facilitated the exchange of slides because they had stopped working, after being disrupted by the breakage of slides in the mail. Often, it is in these moments of disruption or breakdown that infrastructures become more noticeable. In the words of Star and Bowker, disruptions are one way of effecting an "infrastructural inversion," a laying-bare of infrastructures, making these infrastructures visible not only to the historical actors but also to the historian.[69]

This dissertation argues that infrastructural inversion can also help us understand how microscopists generated craft knowledge at a distance. Craftspeople like Mary Ann Booth and many other historical actors in this dissertation depended on infrastructures to exchange a host of diverse objects, ranging from notebooks to slides, instruments and (living) microscope specimens. In trying to circulate such a diverse range of artefacts across long distances, microscopists had to make sure that both their skills in microscopy and infrastructures were perfectly attuned to the task. As I will show, a microscopist's skill in making observations, preparations or instruments was inseparable from their skill in building and using

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[66] These reports were signed by "Queen Mab," probably another of Booth's pseudonyms. Chapter Three elaborates on Booth and the American Postal Microscopical Club.

[67] The question of how female writers made a space for themselves in the nineteenth-century periodical press has been much discussed, for example in Laurel Brake, *Subjugated Knowledges: Journalism, Gender and Literature, in the Nineteenth Century* (Basingstoke: Macmillan, 1994); Margaret Beetham, "Periodicals and the New Media: Women and Imagined Communities," *Women's Studies International Forum* 29, no. 3 (2006): 231-240; Hilary Fraser, Judith Johnston, and Stephanie Green, *Gender and the Victorian Periodical* (Cambridge: Cambridge University Press, 2003).

[68] Geoffrey C. Bowker and Susan Leigh Star, *Sorting Things Out: Classification and Its Consequences* (Cambridge, MA: MIT Press, 1999), 34.

[69] Ibid.

knowledge infrastructures. Consequently, infrastructural inversion allows us to examine not only infrastructures, but also the craft knowledge that these infrastructures helped microscopists to share. This observation – that acquiring skills in microscopy at a distance meant building infrastructures of making and doing microscopy – will drive much of the analysis of the following chapters.

The next section explains the concept of infrastructure underlying this dissertation in more detail. Drawing on a body of literature dealing with practice and infrastructure, the section further develops the argument that microscopists' infrastructures enabled them to share their craft. The section also explains the intricate relationship between infrastructure and media, with media like the *American Monthly Microscopical Journal*, as well as other periodicals and textbooks, playing an important role in the exchange of craft knowledge of microscopy. After that, I turn to three slightly different concepts of infrastructural inversion that this dissertation builds on: Geoffrey Bowker's understanding of infrastructural inversion as a historiographical decision to regard infrastructure not as resulting from, but as enabling technological innovation; Helena Karasti and Jeanette Blomberg's notion of infrastructural inversion as a set of methods that can expose infrastructures; Wolfgang Kaltenbrunner's concept of infrastructural inversion as a generative resource. Karasti and Blomberg's strategies of laying bare infrastructure organise the historical chapters in this dissertation, whereas Kaltenbrunner's concept informs a reflection on my own use of infrastructure as a historical researcher in the final chapter.

Defining Infrastructure

The letter sent to the American *Monthly Microscopical Journal* by Mary Ann Booth provides a good example of the kinds of infrastructure studied in this dissertation. My focus lies on microscopists' communication and trade infrastructures, such as the postal system that made it possible for microscopists like Booth to mail their slides, private correspondence and commercial trade networks, print technologies, and microscopy books and periodicals. This dissertation thus contributes to a growing literature in the history of science that puts the logistics of knowledge exchange centre stage. Mareike Vennen, for example, has demonstrated that the global trade in aquatic animals in the second half of the nineteenth century shaped what was known about the animals exchanged, as gaining knowledge about how to keep those animals alive during transport was prioritised.[70] Anne Coote, Alison Haynes, Jude Philp and Simon Ville have broadly argued that in the nineteenth century "advances in science, collecting and commerce generated mutual benefits," requiring historians to study the "interaction of scientific knowledge, the

[70] See Mareike Vennen, *Das Aquarium: Praktiken, Techniken und Medien der Wissensproduktion (1840-1910)* (Göttingen: Wallstein Verlag, 2018).

technologies of transport and preservation, and the modernization of commercial practices."[71] In a similar vein, Dániel Margócsy, in his book on entrepreneurial science in the Dutch Golden Age, contends that trade networks "did not only provide an infrastructure for long-distance scientific exchange, they also shaped how science was done."[72] In order to gain a better theoretical understanding of how infrastructures "shaped how science was done," it is helpful to draw on the rich literature produced by scholars in infrastructure studies over the last couple of decades.

Building on the 1990s' work of Geoffrey Bowker, Susan Leigh Star and Karen Ruhleder, I conceive of infrastructure as something more than a material scaffold on which other things run or operate. Infrastructure is a relational, "negotiated order" which makes it possible for technologies, organisational resources, work routines and communities of users to function together.[73] According to Star and Ruhleder, infrastructure emerges in practice with the following dimensions.[74] Infrastructure is 1) embedded in "other structures, social arrangements and technologies," 2) transparent only as long as it works and to those familiar with it, 3) infrastructure has a spatial and/or temporal scope that goes beyond a single event, 4) the use of infrastructure is learned through membership in a community of practice, and 5) infrastructure shapes and is shaped by conventions of practice.[75]

All those characteristics apply to the infrastructures microscopists built in the late nineteenth century. They used existing structures, like the postal system and established scientific periodicals, to exchange observations and specimens on a regular basis. Although these existing structures imposed some of their own standards on microscopists' infrastructures, microscopists were able to adapt them to the needs of their community to some degree, for instance by launching new journals, developing low-cost printing technologies, or petitioning to change postal laws. Also, as suggested by Star and Ruhleder, microscopists' infrastructures shaped and were shaped by conventions of practice. Microscopists learned those conventions as part of their membership in the microscopy community. Both the practice and community element in Star and Ruhleder's definition of infrastructure continue to attract much scholarly attention in infrastructure studies, and both are important in answering the question of how microscopy skills travelled. The sociologist Elizabeth Shove, historian Frank Trentmann and human geographer Matt Watson have stressed the role of practice in infrastructure by defining

[71] Anne Coote et al., "When Commerce, Science, and Leisure Collaborated," 320.
[72] Dániel Margócsy, *Commercial Visions: Science, Trade, and Visual Culture in the Dutch Golden Age* (Chicago: University of Chicago Press, 2014), 15.
[73] Bowker and Star, *Sorting Things Out*, 34.
[74] Star and Ruhleder's definition of infrastructure is based on their insight that "infrastructure is something that emerges for people in practice," prompting us to ask "when" is infrastructure, instead of "what" is infrastructure. Star and Ruhleder, "Steps toward an Ecology of Infrastructure," 112.
[75] Ibid., 113. My list of properties follows Geoffrey Bowker's summary of Star and Ruhleder's definition. See Geoffrey C. Bowker, "The History of Information Infrastructures: The Case of the International Classification of Diseases," *Information Processing & Management* 32, no. 1 (1996): 49.

infrastructures as “material arrangements that enable and become integral to the enactment of specific practices.”[76] If we adopt a broad definition of practice as a pattern of actions that is “reproduced through recurrent performance,” then this includes scientific practices such as making observations through the microscope and recording them, as well as the production of slides and instruments.[77] Or, as the historian of science Jim Endersby has argued, making and exchanging scientific specimens – “carefully crafted artefacts” – are crucial scientific practices and part and parcel of the production of scientific knowledge.[78] Therefore, Shove, Trentmann and Watson’s concept of practice and infrastructure can be extended to include not only mundane practices, but also the skilled practices of microscopists, with infrastructures “enabling and becoming integral to” those practices. As we shall see, material infrastructures of making and doing microscopy helped the historical actors discussed in this dissertation acquire skills in preparing and observing microscope specimens, and producing scientific instruments, especially when those actors could not be co-present.

Microscopists’ infrastructures were also entangled with questions concerning scientific authority and membership in the microscopy community, which is in line with Star and Ruhleder’s observation that the use of infrastructure is learned through membership in a community of practice. Janet Vertesi has studied how infrastructures and membership co-evolve in scientific communities.[79] She argues that it is the practitioners’ ability to work across multiple information infrastructures that defines their membership in the community. Vertesi introduces an analytical vocabulary of infrastructural “seams,” observing “how actors skilfully produce moments of alignment between and across systems: not fitting distinct pieces together into a stable whole, but producing fleeting moments of alignment suited to particular tasks with materials ready-to-hand.”[80] In the case of late-nineteenth-century microscopists, aligning infrastructures required a range of skills: knowing how to reply to letters published in correspondence columns, how to exchange slides and keep track of where they went with the help of periodicals, how to copy illustrations and reprint them in other publications, or how to reproduce experiments and document them in print. As the following chapters show, this

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[76] Elizabeth Shove, Frank Trentmann, and Matt Watson, "Introduction – Infrastructures in Practice: The Evolution of Demand in Networked Societies," in *Infrastructures in Practice: The Dynamics of Demand in Networked Societies*, ed. Elizabeth Shove and Frank Trentmann (London: Routledge, 2019), 4. See also Elizabeth Shove, "Matters of Practice," in *The Nexus of Practices: Connections, Constellations, Practitioners*, ed. Allison Hui, Theodore Schatzki, and Elizabeth Shove (London: Routledge, 2017), 155-168.
[77] Elizabeth Shove, Mika Pantzar, and Matt Watson, *The Dynamics of Social Practice: Everyday Life and How It Changes* (Los Angeles: Sage, 2012), 8.
[78] Jim Endersby, *Imperial Nature: Joseph Hooker and the Practices of Victorian Science* (Chicago: University of Chicago Press, 2008), 16. This is also in line with the argument in Secord, "Knowledge in Transit."
[79] Janet Vertesi, "Seamful Spaces: Heterogeneous Infrastructures in Interaction," *Science, Technology, & Human Values* 39, no. 2 (2014): 264-284.
[80] Vertesi, "Seamful Spaces," 268.

working at the seams of infrastructures, knowing how to temporarily align them, was indeed integral to both being a member in the microscopy community and sharing craft knowledge of microscopy.

Although some members of the microscopy community could meet in person at society gatherings or field excursions, many microscopists relied on circulating media, such as periodicals, trade catalogues and personal correspondence, to both discuss the use of the microscope and gain a sense of community. As the number of popular science periodicals surged in Great Britain in the 1860s and, around a decade later, in the US, it became easier for microscopists to build a "virtual community."[81] Geoff Belknap describes this community as partially real, gathering in physical spaces, and partially imagined in the pages of periodicals:

> While communities were made, and partially imagined, through correspondence networks, meetings at learned societies, the circulation of pamphlets and offprints, and the publication of other forms of scholarly communication, it was only the periodical that brought together all these forms of community building into one, serially constructed, textual and visual space.[82]

Belknap argues that the meetings of natural history societies extended into the pages of their periodicals, one of his most notable examples being a printer demonstrating a printing technology at a society meeting and continuing his performance in print – after the meeting, the printer used his technology to print some of the pages in the society's periodical.[83]

Media were a crucial part of microscopists' knowledge infrastructures, providing both a sense of community and instructions on how to observe and make microscope specimens through texts and images. As Daniela Bleichmar argues in her history of eighteenth-century botanical trade and travel, botanists travelling between Europe and the Americas were connected by circulating plant illustrations, with illustrated books helping to "define and arbitrate a community of competent and relevant practitioners."[84] Scientific observation was a "multimedia affair," depending on a "constant triangulation among image, text, and specimen."[85] Likewise, microscopy illustrations were not only records of what a micros-

[81] For a study of the surge in popular science periodicals at the time, see Lightman, "Transformations of Nineteenth-Century Publishing." Leary uses the term "virtual community" to describe a nineteenth-century community of reader-contributors in "A Victorian Virtual Community."
[82] Geoffrey Belknap, "Illustrating Natural History: Images, Periodicals, and the Making of Nineteenth-Century Scientific Communities," *The British Journal for the History of Science* 51, no. 3 (2018): 5.
[83] Belknap, "Illustrating Natural History," 27.
[84] Daniela Bleichmar, "The Geography of Observation: Distance and Visibility in Eighteenth-Century Botanical Travel," in *Histories of Scientific Observation*, ed. Elizabeth Lunbeck and Lorraine Daston (Chicago: University of Chicago Press, 2011), 385.
[85] Bleichmar, "The Geography of Observation," 375, 385.

copist had observed, and how, but were used alongside the microscope to triangulate observations. Whereas media do not feature prominently in Star and Ruhleder's 1996 article – nor in Bowker and Star's *Sorting Things Out* – including media in my analysis of microscopists' knowledge infrastructures does not go against those authors' concept of infrastructure. As Gabriele Schabacher reminds us, the notion of media as infrastructure can be traced back to Marshall McLuhan's work on transport and transformation.[86] Star and Bowker, too, have recently acknowledged infrastructure as an important, but often neglected, aspect of communication and media studies.[87] Since Star and Bowker make their observation in relation to new media, it almost seems as if media had to turn digital to gain more attention from infrastructure scholars.

Studying late-nineteenth-century media from the perspective of infrastructure helps us to, in Shove, Trentmann and Watson's words, think of those media as "material arrangements that enable and become integral to the enactment of specific practices."[88] This is also increasingly recognised in the literature that deals with paper tools and technologies in the history of science, which has turned to the materiality of information and the many ways paper is put to use in the production of knowledge.[89] For example, Miles Ogborn, although he does not use the term "infrastructure," has studied how the English East India Company exerted power over its trade network with the help of different material forms of writing.[90] Interestingly, Boris Jardine, in his review of the literature on paper tools, observes that "paper can be both transparent and opaque depending on the social world it inhabits and helps to constitute," which is reminiscent of Star and Ruhleder's claim that infrastructure is transparent only as long as it works and to those familiar with it.[91] In conceiving of microscopists' books, drawings, periodicals, notebooks and letters as travelling paper tools, the following chapters explore how media became tools of acquiring craft knowledge and how they afforded the skilled practices of microscopists.

[86] See Gabriele Schabacher, "Transport und Transformation bei McLuhan," in *Medien Verstehen: Marshall McLuhans Understanding Media*, ed. Till A. Heilmann and Jens Schröter (Lüneburg: Messon Press, 2017), 59-84. Schabacher refers to Star and Ruhleder's work in explaining the (in)visibility of infrastructure.

[87] Star and Bowker do acknowledge that there are many histories of one type of communication infrastructure, one of the best-known being Thomas Parke Hughes, *Networks of Power: Electrification in Western Society, 1880-1930* (Baltimore: Johns Hopkins University Press, 1983). But the two scholars criticise the lack of attention to infrastructure in more general media histories. Susan Leigh Star and Geoffrey C. Bowker, "How to Infrastructure," in *Handbook of New Media: Social Shaping and Consequences of ICTS*, ed. Leah A. Lievrouw and Sonia Livingstone (London: Sage, 2006), 230-245.

[88] Elizabeth Shove and Frank Trentmann, eds., *Infrastructures in Practice: The Dynamics of Demand in Networked Societies* (London and New York: Routledge, 2019).

[89] For a comprehensive review of this literature, see Boris Jardine, "State of the Field: Paper Tools," *Studies in History and Philosophy of Science Part A* 64 (2017): 53-63.

[90] See Miles Ogborn, *Indian Ink: Script and Print in the Making of the English East India Company* (Chicago: University of Chicago Press, 2008).

[91] Jardine, "State of the Field: Paper Tools," 53.

After elaborating the notion of infrastructure underlying this dissertation, and how it shapes and is shaped by scientific practices and communities, the question remains of how to analyse microscopists' infrastructures and the exchange of craft knowledge they facilitated. Therefore, the next section enlarges on how to study infrastructure, focusing on three different approaches to exposing and examining infrastructure, or three ways of achieving "infrastructural inversion," which organise the following chapters.

Studying Infrastructure

Bowker developed the concept of infrastructural inversion in a 1994 chapter dealing with the "information revolution" and the nineteenth- and twentieth-century infrastructures that helped to make information the defining element of our age.[92] Bowker and Star's *Sorting Things Out* took up this idea of infrastructural inversion, describing it as a way of foregrounding and analysing infrastructure.[93] Since then, infrastructural inversion has become a common method in ethnographic and historical studies of infrastructure, a method that informs my own analysis and structures the chapters of this dissertation. More recently, infrastructure scholars have begun to emphasise the performative dimension of researching infrastructure, looking into how researchers construct infrastructure as they study it. This performative concept, too, inspires my analysis, in particular my concluding reflection on the *Worlds of Wonder* citizen science project, which not only helped me collect data, but also became a virtual scientific community with its own infrastructures.

Before turning to the more common notion of infrastructural inversion as a method to expose and examine infrastructure, it seems worth enlarging on Bowker's idea outlined in his chapter of 1994. Bowker originally envisioned infrastructural inversion as a profound historiographical gestalt switch. He suggested to conceive of historical changes commonly ascribed to some arguably groundbreaking technology as resulting from the infrastructures permitting the development of that technology. Bowker writes:

> Take a claim that has been made by advocates of a particular piece of science/technology, then look at the infrastructural changes that preceded or accompanied the effects claimed and see if they are sufficient to explain

[92] See Geoffrey C. Bowker, "Information Mythology: The World of/as Information," in *Information Acumen: The Understanding and Use of Knowledge in Modern Business*, ed. Lisa Bud-Frierman (London and New York: Routledge, 1994), 231-247. I would like to thank Jacob Ward for pointing me to Bowker's 1994 chapter, and the notion of infrastructural inversion as a historiographical decision, at the 2020 MUSTS Summer Harvest workshop.
[93] See Bowker and Star, *Sorting Things Out*.

> those effects – then ask how the initial claim came a posteriori to be seen as reasonable.[94]

Bowker thus makes a case for focusing on infrastructure to undermine technologically determinist arguments. Since Bowker, like Star and Ruhleder, thinks of infrastructure not as a technological scaffold but as a form of organisation work, his infrastructural inversion does not replace one technology with another in writing the history of science and technology but centres on the work required to build infrastructure.

Notably, Bowker's concept asks historians to move beyond writing histories of specific infrastructures, such as the telephone, telegraph or electric grid, and consider the role of infrastructure in the emergence of new technologies.[95] Whereas histories of single infrastructures have become rather common, histories that take Bowker's idea of infrastructural inversion seriously, looking at how a whole range of infrastructures enable technological developments, remain far and few between.[96] Focusing on the infrastructural emergence of microscopy in the second half of the nineteenth century, this dissertation follows up on Bowker's historiographical suggestion.[97] It argues that to explain the rise of microscopy, historians need to move beyond examining lab scientists' epistemological debates around microscopy and turn to the infrastructures that enabled microscopists to share their methods widely.

These infrastructures consisted of note- and sketchbooks, science journals, chain-letter-systems, at-home printing presses, trade papers and catalogues, and, importantly, relied on the postal system. Thus, when we look at the spread of observation and preparation methods in microscopy in the late nineteenth century, people and objects come to the fore that are under-researched in the history of science, but that are crucial if we want to understand what it took for skills to travel. This may seem to merely reiterate Steven Shapin's long-standing argument to consider the invisible technicians in the history of science.[98] However, the infrastructural inversion undertaken in this dissertation asks us to acknowledge the importance of craftspeople not only as scientific assistants in the lab or field, but as builders of international knowledge infrastructures, which reached just as far as

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[94] Bowker, "Information Mythology," 235.
[95] Star in Bowker renewed their suggestion in "How to Infrastructure."
[96] In 2006, Bowker and Star still had to resort to an early art historical study as their prime example of how communities emerge through intersecting infrastructures, Howard S. Becker, *Art Worlds* (Berkeley, CA: University of California Press, 1982). Recently, there has been more attention for intersecting infrastructures in STS, see, for example, Vertesi, "Seamful Spaces."
[97] Following Soden and Paylen's paper on mapmakers working on the response to the 2015 Nepal earthquakes, I use the term "infrastructural emergence" to describe infrastructure that emerges "through [users'] appropriation of available resources and the creation of new ones." Robert Soden and Leysia Palen, "Infrastructure in the Wild: What Mapping in Post-Earthquake Nepal Reveals About Infrastructural Emergence" (Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems, San Jose, California, USA, Association for Computing Machinery, 2016).
[98] See Steven Shapin, "The Invisible Technician," *American Scientist* 77, no. 6 (1989): 554-563.

the correspondence networks of professional scientists that historians of nineteenth-century science have long paid more attention to.

After Bowker introduced his concept of infrastructural inversion as a historiographical turn towards infrastructure in 1994, Bowker and Star's work became more concerned with infrastructural inversion as an ethnographic tool to defamiliarise infrastructures and make them more discernible, "a struggle against the tendency of infrastructure to disappear (except when breaking down)."[99] In *Sorting Things Out*, the authors provide their readers with what they call "methodological themes" that help researchers direct their attention to infrastructure. These methodological themes point towards the ubiquity and materiality of infrastructure, its historical contingence – the question of whose standards an infrastructure has come to enforce and why – and the everyday negotiations through which some users manage to implement their standards in infrastructural design.[100] Over the past two decades, Bowker and Star's considerations have been taken up and further developed by a host of researchers in infrastructure studies.[101]

However, as Helena Karasti and Jeanette Blomberg observe, concrete instructions on how to achieve infrastructural inversion that go beyond Bowker and Star's methodological themes have remained scarce in the literature. Karasti and Blomberg have sought to remedy this lack of practical instruction by reviewing cases of infrastructural inversion in infrastructure studies and distilling strategies of how to analyse infrastructure. The two scholars formulate three ways of attaining infrastructural inversion: "investigating moments of breakdown, following how members themselves engage in activities of infrastructural inversion, and following infrastructural traces in the material and technical environments."[102] The first, investigating moments of controversy or breakdown, is probably the most widely known strategy, building on Bowker and Star's observation that infrastructure becomes more noticeable when it stops functioning. The second, looking at the actors' attempts at infrastructural inversion, is based on the premise that an infrastructure always remains evident to at least some of its users: its maintainers, people whose task it is to build and maintain infrastructure.[103] The third strategy,

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[99] Bowker and Star, *Sorting Things Out*, 34.
[100] Ibid., 37ff.
[101] The infrastructure scholarship following Bowker, Star and Ruhleder's work cannot possibly be covered in a footnote, but the following publications give an overview of the state of the art in infrastructure studies: Christine L. Borgman et al., "Our Knowledge of Knowledge Infrastructures: Lessons Learned and Future Directions," *Report of Knowledge Infrastructures Workshop* 27 (2020); Paul N. Edwards et al., "Introduction: An Agenda for Infrastructure Studies," *Journal of the Association for Information Systems* 10, no. 5 (2009): 364-374; Andrew Barry, "The Material Politics of Infrastructure," in *TechnoScienceSociety: Technological Reconfigurations of Science and Society*, ed. Sabine Maasen, Sascha Dickel, and Christoph Schneider (Berlin: Springer, 2020), 91-109.
[102] Helena Karasti and Jeanette Blomberg, "Studying Infrastructuring Ethnographically," *Computer Supported Cooperative Work (CSCW)* 27, no. 2 (2018): 251.
[103] This strategy matches Star and Ruhleder's observation that infrastructure may well remain visible to some of its users. Star and Ruhleder, "Steps toward an Ecology of Infrastructure."

following infrastructural traces, is similar to the object biography approach discussed earlier in this chapter. It means reconstructing the movement of objects through infrastructure, preferably objects that document or bear traces of collaborative practices. Together, Karasti and Blomberg's three ways of infrastructural inversion structure the chapters of this dissertation.

The Chapters

Building on Karasti and Blomberg's strategies, the chapters in this dissertation achieve infrastructural inversion by following artefacts (Chapter Two), examining historical actors' attempts at infrastructural inversion (Chapter Three), and studying a moment of disruption or conflict (Chapter Four). Each chapter looks at a different subgroup of microscopists within the microscopy community, moving from a very loose community of observers connected mainly through citational and drawing practices to more tight-knit postal networks, and finally the close relationship between the physicist Ernst Abbe and his correspondents in the RMS, who met in person a few times. Since these groups of microscopists and their knowledge infrastructures crossed national boundaries, so do the chapters. The dissertation first focuses on British microscopists and their observations but soon branches out to continental European and American observers and slide makers, before turning to a controversy that involved American, British, and German microscopists. The chapters are only roughly chronological. Chapter Two begins in the 1850s but follows the travels of microscopy illustrations throughout the second half of the nineteenth century. Chapter Three focuses on the 1870s, when postal microscopy societies were founded and gained most of their members, whereas Chapter Four traces a controversy that began in the 1870s but continued into the 1880s.

Chapter Two adopts Karasti and Blomberg's approach of following artefacts as they move through infrastructure. Beginning in the 1850s, the chapter follows a set of microscopy artefacts: illustrations of a phylum of microscopic animals called rotifers, or wheel animals. The *Worlds of Wonder* citizen science project made it possible to follow these rotifer illustrations and their makers, and identify reproductions, which, being passed around and adapted by microscopists, contain the traces of collaborative practices Karasti and Blomberg advise us to look for. Tracing rotifer illustrations through private sketchbooks, pamphlets and publications in Britain, as well as some of their reproductions on the European continent and in the United States until the end of the century, the chapter looks at how novel printing technologies and print distribution infrastructures enabled microscopists to share their observations, and at the same time develop their observational skills. At a time when the reproduction of scientific publications was hardly restricted by international copyright law, scissors-and-paste printing abounded, with publishers reusing both texts and illustrations that had been published elsewhere. Scissors-and-paste printing made it possible for microscopists to adapt microscopy illustrations as part of their observational practice, for example by recombining illustrations with new texts and images. In that sense, rotifer illustrations were never quite stabilised through print. They continued to be used in (and were changed by) a researchers' observational practice, much like the messy, private sketches Omar Nasim calls "working images," allowing observers to probe with the hand what is seen with the eye.[104] The chapter shows that observation was a craft that depended on the hand as much as the eye, making craftspeople, such as illustrators and natural history dealers, vital in sharing microscopy observations. For instance, natural history dealers provided science educators with living microscope specimens to be observed in the classroom, and with illustrations and written descriptions to help interpret observations made with the microscope. This gave craftspeople an opportunity to shape not only what students of the life sciences saw through the microscope, but also how they observed the specimens they received.

Chapter Three turns to a group of historical actors whose task it was to build and maintain the infrastructures microscopists relied on to produce and exchange microscope slides. The chapter looks at the British Postal Microscopical Society and the American Postal Microscopical Club, whose officers and secretaries built postal networks that enabled their members to pass on slides and notebooks following a chain-letter system. Educating their members on how to make microscope slides was the primary purpose of the two postal microscopy organisations. The officers of the postal society and club articulated the work it took to establish their chain-letter networks in their notebooks, publications, lists of members, and in maps of postal circuits. Both organisations frequently addressed the infrastructures organising their work, which, as explained by Karasti and Blomberg, makes it easier for historians to research them. There was a sense among the members of the two postal organisations that their craft knowledge of how to make permanent slides was difficult to share without physical meetings. In response, they conceived of alternative ways to share their skills, which included the making of sketches in addition to texts, as well as attempts at reverse-engineering slides. Yet the society and club's postal networks remained fragile, depending on the reliability of their members to forward packages and keep the exchange going, while making sure that the slides forwarded would not break in transit. In order to deal with these vulnerabilities, regular reports on the activities of the postal society and club were published in microscopy periodicals. This helped to institutionalise the two organisations, centralise the postal exchanges, discipline unreli-

[104] See Omar W. Nasim, *Observing by Hand: Sketching the Nebulae in the Nineteenth Century* (Chicago: University of Chicago Press, 2013).

able or careless members, and share recommendations for the preparation of microscope specimens. The postal society and club managed to connect their members for at least several decades – the British Postal Microscopical Society exists to this day – and over time, the ability of a slide to travel postal networks without breaking became proof of its durability and helped to set the benchmark for other permanent preparations.

Chapter Four investigates a moment of controversy or breakdown, focusing on two stages of a fierce transatlantic debate in the 1870s, the "battle of the glasses." The battle was fought over the ultimate limit of resolution in a light microscope, which an American microscope lens had pushed further than many British microscopists deemed possible. The controversy not only exposed but directly affected microscopists' knowledge infrastructures, asking them to reconsider and adapt established communication mechanisms. At the same time, the controversy gave the German physicist Ernst Abbe an opportunity to become involved in the British microscopy community, share his research through the knowledge infrastructures that emerged during the controversy, and profit from innovations conceived of by his British correspondents. The chapter builds on the concept of "amateurisation," a term used by Sam Alberti and others to describe British amateurs fashioning a new identity for themselves in the 1860s and 1870s. It shows that the process of amateurisation went hand in hand with the establishment of infrastructures that served as a testbed for innovation in scientific instrument making – Ernst Abbe, working for the Zeiss company, profited from the infrastructures established by members of the RMS. Moreover, bringing together work in controversy studies and innovation studies, I argue that historians of science have studied controversy and innovation in some depth, but they have been less concerned with controversy *in* innovation. The history of the "battle of the glasses" shows that innovation can be deeply controversial, and that controversies shape the infrastructures that facilitate user innovation.

While the three historical chapters in this dissertation use infrastructural inversion to trace late-nineteenth-century infrastructures, Chapter Five draws together the main findings of the previous chapters and takes a closer look at the decline of the microscopy community around 1900. The chapter weaves together the four thematic threads that run through the historical chapters – craft knowledge, infrastructure, community-building, and science education – and provides answers to the question of how geographically dispersed microscopists acquired skills in microscopy. The chapter also reflects on the performative dimension of studying infrastructure. As researchers, we decide which infrastructures are worth following in our analyses, always foregrounding only some while others remain in the background. Our research thus reifies and maintains the infrastructures we study. As Karasti and Blomberg put it, "the object of inquiry is continually being delineated through engagement with the phenomenon."[105] On the one hand, being aware of the performative dimension of studying infrastructure reminds us that our research always constructs the past or present it describes. On the other hand, scholars in infrastructure studies have more recently come to cherish the performativity of their work, regarding it as an opportunity to imagine and realise new infrastructures.

Wolfgang Kaltenbrunner has further developed this notion of performativity, describing infrastructural inversion as a "generative resource."[106] In his view, infrastructural inversion is an invaluable approach to both study and build alternative infrastructures. Infrastructural inversion can be a creative tool, a way of reimagining and reconfiguring existing infrastructures. Volkmar Pipek, Helena Karasti and Geoffrey Bowker support Kaltenbrunner's approach by proposing to study "infrastructuring," a "relational and processual (in-the-making) perspective and/or design-oriented interest towards Information Infrastructures."[107] The three scholars argue that although there has been no lack of attention for infrastructure, much of the creative potential of infrastructural inversion remains to be explored. Applying Kaltenbrunner's concept of infrastructural inversion as a generative resource to this dissertation means to reflect on the generative potential of the infrastructures I built in my research, especially the ones I developed as part of my citizen science project. The final chapter therefore examines how my research into late-nineteenth-century infrastructures shaped *Worlds of Wonder*, and vice versa, concluding this dissertation with a discussion of the past and present of participatory science and imagining its possible futures.

[105] See Karasti and Blomberg, "Studying Infrastructuring Ethnographically."
[106] See Wolfgang Kaltenbrunner, "Infrastructural Inversion as a Generative Resource in Digital Scholarship," *Science as Culture* 24, no. 1 (2015): 1-23.
[107] Volkmar Pipek, Helena Karasti, and Geoffrey C. Bowker, "A Preface to 'Infrastructuring and Collaborative Design'," *Computer Supported Cooperative Work (CSCW)* 26, no. 1 (2017): 1. Pipek, Karasti and Bowker edited three *CSCW* special issues dedicated to infrastructuring in 2017 and 2018.

2 Picturing Pond Life: The Reuse of Rotifer Illustrations

In 1857, the *North American Medico-Chirurgical Review* published a scathing assessment of a microscopy handbook written by the English physician Jabez Hogg. The journal criticised Hogg for copying entire paragraphs "verbatim et literatim" from an American microscopy manual, Joseph Wythe's *The Microscopist* from 1851. Although the anonymous reviewer admitted that every microscopy handbook was, to some extent, a compilation of previous books, Hogg was attacked for plagiarising Wythe's work without even mentioning it as his source – "a Hogg-ish proceeding certainly."[1] "Scissors-and-paste" publishing, reprinting material that had appeared elsewhere, was a common practice in the expanding nineteenth-century literary market, as international copyright regulations were either non-existent or rarely enforced.[2] Many microscopy publications included not only reprinted text but also illustrations, with illustrated plates being much cheaper for publishers to reuse than produce themselves.[3] Indeed, Hogg's own work was treated in the same way that he had used Wythe's. By the time the critical review of Hogg's work was published in the *North American Medico-Chirurgical Review* in 1857, the frontispiece of Hogg's book had already been reprinted in a German microscopy handbook by the botanist Moritz Willkomm (Fig. 2.1 and 2.2). A correspondent of the *English Mechanic,* commenting on illustrations of the green algae *Volvox globator* he had encountered in various publications, wrote in 1877: "Almost every picture seems to be printed from one block. I do not believe we have more than two original drawings published in any books."[4]

While controversial at times, scissors-and-paste publishing facilitated the production of cheap illustrated microscopy handbooks, which poured into the American and European literary markets in the second half of the nineteenth century. Both text and images in those publications provided instruction on how to observe microscope specimens, which was a difficult task especially for beginners. Examining a specimen required the microscopist to use the right source of light at just the right angle, choose a microscope objective with the appropriate resolving

[1] "Art. VIII. – The Microscope. Its History, Construction, and Application. By Jabez Hogg, M.R.C.S. London," *North American Medico-Chirurgical Review* 1 (1857): 572.

[2] See Stephan Pigeon, "Steal It, Change It, Print It: Transatlantic Scissors-and-Paste Journalism in the Ladies' Treasury, 1857–1895," *Journal of Victorian Culture* 22, no. 1 (2017): 24-39. It was only after the Berne Convention (1886) and the American Chace Act (1891) that copyright laws were enforced internationally.

[3] See Rose Roberto, "Democratising Knowledge and Visualising Progress: Illustrations from Chambers's Encyclopaedia, 1859-1892" (PhD dissertation, University of Reading, 2018); Nick Hopwood, *Haeckel's Embryos: Images, Evolution, and Fraud* (Chicago: University of Chicago Press, 2015).

[4] Essex, "Volvox Globator," *English Mechanic and World of Science* 25 (1877): 487.

power, and carefully fix the specimen on the stage without crushing it. The microscope had to be focused without losing the specimen out of sight, and when a living animal was observed, this came with the additional difficulty of restricting the animal's movement while keeping it alive. Finally, the observer had to be able to interpret what he or she saw through the microscope. To that end, microscope users often at the same time observed illustrations of their specimens, constantly comparing what they saw through the microscope with observations others had recorded before them.

Figure 2.1 Frontispiece in Jabez Hogg's *The Microscope* (1854). Image from the Biodiversity Heritage Library. Contributed by the University of Toronto Thomas Fisher Rare Book Library.

Figure 2.2 Moritz Willkomm's *Die Wunder des Mikroskops* (1856). Image from the Internet Archive. Contributed by the Wellcome Library.

Bernard Lightman has long called on historians of nineteenth-century science to take a closer look at the abundant visual culture of Victorian microscopy.[5] To date, however, the relevant literature mainly relies on textual sources, notable exceptions being Geoff Belknap's analysis of the collaborative expertise that went into producing illustrations for the *Journal of the Quekett Microscopical Club* and Lightman's study of the microscopy illustrations of John George Wood, a natural

[5] Lightman, "The Microscopic World."

theologian.[6] However, neither Belknap nor Lightman have considered the possibility of microscopy images moving between media due to scissors-and-paste publishing, and how their circulation may have shaped the observational practices of microscopists. Nick Hopwood, on the other hand, has closely followed the circulation of Ernst Haeckel's embryo illustrations as scientific and public controversies unfolded around them, but has been less concerned with the question of how circulating illustrations helped their viewers develop scientific skills.[7]

This chapter argues that reproducing illustrations of microscope specimens was crucial in helping microscopists acquire observational skills. Microscopists not only drew what they saw through the microscope, but they also meticulously copied – by hand and in print – observations others had made before them. In fact, the act of observing a specimen reached far beyond the moment it was placed under the microscope, as microscope users examined illustrations made by previous observers just as closely as the specimen itself. When an illustration was reprinted, it entered into conversation with new texts and images, which made it possible for scientific authors to promote their own observational practices and present themselves as knowledgeable, while building on the authority of previous observers. At the same time, microscopists were aware that their illustrations were affected by the technologies used to reproduce them, and that, for example, the wide reach of reproductions made with cheap printing techniques had to be weighed against the accuracy of more expensive prints. If we take James Secord's advice to "think about knowledge-making itself as a form of communicative action," then developing observational skills in microscopy in the late nineteenth century meant to develop skills in sharing observations, too, and build knowledge infrastructures to reproduce illustrations of microscope specimens.

From a methodological perspective, we can expose the infrastructures used and built by microscopists to share observations of microscopic life by tracing the circulation of illustrations. As explained in the previous chapter, one way of achieving "infrastructural inversion" – "learning to look closely at technologies and arrangements that, by design and by habit, tend to fade into the woodwork" – is to follow an object as it moves through infrastructure.[8] Karasti and Blomberg contend that objects which bear traces of their exchange within a community of practitioners are particularly well suited for an infrastructural analysis, such as collaborative documents, or version histories. Late-nineteenth-century reproductions of microscopy illustrations often carried traces of their appearance in other publications

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[6] See Belknap, "Illustrating Natural History;" Bernard Lightman, "The Visual Theology of Victorian Popularizers of Science: From Reverent Eye to Chemical Retina," *Isis* 91, no. 4 (2000): 651-680. In *The Microscope and the Eye* Jutta Schickore points her readers to some microscopy illustrations, too, but these are not central to her argument.

[7] See Hopwood, *Haeckel's Embryos*. For a close study of how eighteenth-century botanists copied and circulated illustrations, see Kärin Nickelsen, *Draughtsmen, Botanists and Nature: The Construction of Eighteenth-Century Botanical Illustrations* (Dordrecht: Springer Netherlands, 2006).

[8] Bowker and Star, *Sorting Things Out*, 34.

and encounters with previous observers, allowing us to expose microscopists' knowledge infrastructures. Since this chapter is mainly concerned with illustrations, it draws on concepts of image circulation put forward by researchers in the field of media studies and communication.[9]

The media studies scholar Laurie Gries has developed the method of "iconographic tracking" to trace viral images online. According to her definition, iconographic tracking means following an image through its various material transformations and encounters with people and objects by combining traditional qualitative research with online search tools.[10] Gries argues that through iconographic tracking, researchers can reconstruct an image's "occasions of use."[11] Although one must be careful not to conflate nineteenth-century reproductions of illustrations and present-day viral images, the many digitised nineteenth-century sources which are readily available today lend themselves to being analysed with digital methods.[12] In line with Gries' approach, this chapter combines traditional qualitative research – the close reading of digitised and non-digitised archival materials – with the distant reading of digitised sources and crowdsourced digital data.

The chapter draws on data collected through the *Science Gossip* citizen science project and my own *Worlds of Wonder* project. Like *Worlds of Wonder*, *Science Gossip*, run by the ConSciCom research group on Zooniverse from 2015 to 2019, invited citizen scientists to classify illustrations in nineteenth-century natural history periodicals and identify their producers.[13] The data collected from three British microscopy periodicals, *Hardwicke's Science Gossip*, the *Journal of the Royal Microscopical Society* and the *Journal of the Quekett Microscopical Club,* were particularly useful for my research.[14] The *Worlds of Wonder* project produced

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[9] Some notable works include Cara Finnegan, "Studying Visual Modes of Public Address. Lewis Hine's Progressive-Era Child Labor Rhetoric," in *The Handbook of Rhetoric and Public Address* ed. Shawn J. Parry-Giles and J. Michael Hogan (Malden, MA: Wiley-Blackwell, 2010), 250-270; Lester C. Olson, *Benjamin Franklin's Vision of American Community: A Study in Rhetorical Iconology* (Columbia, SC: University of South Carolina Press, 2004); Laurie E. Gries, *Still Life with Rhetoric: A New Materialist Approach for Visual Rhetorics* (Logan, UT: Utah State University Press, 2015).

[10] Laurie Gries follows a viral image as it "shifts from, among other things, an illustration to propaganda to a genre of critique to a touchstone for copyright law and remix" in her article Laurie E. Gries, "Iconographic Tracking: A Digital Research Method for Visual Rhetoric and Circulation Studies," *Computers and Composition* 30, no. 4 (2013): 338. For a detailed description of her methodology, see Gries, *Still Life with Rhetoric.*

[11] Gries, "Iconographic Tracking," 338.

[12] For an overview of the challenges of digitising, and researching digitised, nineteenth-century periodicals and illustrations, see James Mussell, *The Nineteenth-Century Press in the Digital Age* (Basingstoke: Palgrave Macmillan, 2012); Julia Thomas, *Nineteenth-Century Illustration and the Digital* (Basingstoke: Palgrave Macmillan, 2017).

[13] Constructing Scientific Communities – Citizen Science in the 19th and 21st Centuries (ConSciCom, https://conscicom.org/) was an AHRC funded project based at the universities of Leicester and Oxford. Zooniverse is one of the largest web-based citizen science platforms (https://www.zooniverse.org/).

[14] Whereas all nineteenth-century volumes of *Hardwicke's Science Gossip* and the *Journal of the Quekett Microscopical Club* have been analysed by citizen scientists, of the *Journal of the Royal Microscopical Society* only the 1879-1889 (and 1900) volumes have been analysed so far.

complementary data on illustrations in a range of British, American and German microscopy publications, including beginner's handbooks, textbooks, periodicals and hand-drawn flyers. A complete list of publications analysed by the *Worlds of Wonder* citizen scientists has been appended to this dissertation.[15] Together, the two datasets compiled by the *Science Gossip* and *Worlds of Wonder* researchers provide insight into who produced microscopy illustrations, and how collaborations among illustrators, engravers and printers resulted in the illustrations readers of microscopy publications got to see and use in their own studies of microscopic life. The two datasets also make it easier for us to find reproductions of illustrations, either by searching for and comparing illustrations tagged as showing the same specimen, or by filtering the data for illustrations signed by the same illustrator, engraver or printer.

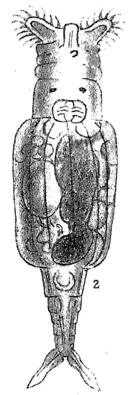

Figure 2.3 Rotifer of the genus *Philodina*, published in *The Journal of the Quekett Microscopical Club*, 1892 (ser. 2, vol. 4, p. 375).

Many of the illustrations classified by the *Science Gossip* and *Worlds of Wonder* citizen scientists show freshwater plants and animals, which could easily be obtained from ponds and puddles and were therefore popular with beginners in microscopy.[16] As the science writer Henry James Slack puts it in the second edition of his *Marvels of Pond-Life* (1871),

> the most fascinating objects are living creatures of sufficient dimensions to be easily understood with moderate magnification; and in no way can

[15] See Appendix B.
[16] For a study of the history of pond life in classroom teaching in the German lands, see Chapter Five in Lynn K. Nyhart, *Modern Nature: The Rise of the Biological Perspective in Germany*. Chicago: University of Chicago Press, 2009.

> objects of this description be so readily obtained, as by devoting an occasional hour to the examination of … little ponds.[17]

A group of aquatic animals especially beloved by researchers of pond life were rotifers, or wheel animals. Rotifers were easy to find and observe and, having mouths and eyes, rotifers inspired affection – some microscopists who kept rotifers in an aquarium at home thought of them as their pets (Fig. 2.3). Rotifers could be found in almost any lake, pond or puddle and, with a size of usually between 0.1 to 0.5 millimetres, could be observed even with cheap microscopes. Rotifer illustrations featured in virtually all beginner's handbooks on freshwater microscopy. Often, these illustrations were reproductions of earlier drawings of rotifers. Through their many reprints, rotifer illustrations travelled far and wide, making them well suited for an analysis of how illustrations helped microscopists make observations. This chapter, therefore, traces the circulation of rotifer illustrations among observers of freshwater life, reconstructing, in Laurie Gries' words, their "occasions of use."

In what follows, I first provide an overview of late-nineteenth-century print culture and the actors directly involved in the production of microscopy illustrations – illustrators, engravers and printers – building on the data crowdsourced by the *Science Gossip* and *Worlds of Wonder* participants. After that, the chapter zooms in on a group of researchers of pond life who produced rotifer illustrations, closely following the circulation of those illustrations mainly within Great Britain, but also tracing some reproductions in Europe and the United States. The chapter concludes by providing answers to the question of how microscopists (re)used illustrations to teach themselves and others how to observe microscopic life.

Illustrating, Engraving, and Printing Microscopy

Since the early time of microscopy in the late seventeenth century, microscopic observation and illustration have been intimately linked. As Sietske Fransen writes, Antoni van Leeuwenhoek's illustrators were close collaborators and witnesses of his observations.[18] When the microscope entered the bourgeois salon in the eighteenth century, microscopy became entrenched in polite culture.[19] Drawing botanical illustrations had long been part of the education of ladies and gentlemen of the higher classes, who began to use the microscope to extend their observations of nature into the subvisible realm.[20] The microscope revealed that even the subvisible world was teeming with life. Observing and drawing what was seen through the

[17] Henry James Slack, *Marvels of Pond-Life; or, a Year's Microscopic Recreations among the Polyps, Infusoria, Rotifers, Water-Bears, and Polyzoa*, 2nd ed. (London: Groombridge and Sons, 1871), iii.
[18] See Fransen, "Antoni Van Leeuwenhoek, His Images and Draughtsmen."
[19] See Schickore, *The Microscope and the Eye*, 17-18.
[20] Ann B. Shteir has published extensively on women artists in botany in the eighteenth and nineteenth centuries, see, for example, Ann B. Shteir, *Cultivating Women, Cultivating Science: Flora's Daughters and Botany in England, 1760-1860* (Baltimore: Johns Hopkins University Press, 1996); Ann

microscope became an exercise in self-improvement, filling the viewer with reverence for God's creation. By the mid-nineteenth century, microscopy was still a pastime of the higher classes but became more accessible to middle-class observers, too. Not only did microscopes become cheaper but illustrations of microscopic life were circulated more widely than ever before.

Historians of print culture generally consider the spread of wood engraving around 1800 a crucial turning point in illustrated print.[21] Unlike woodcuts, wood engravings are cut across the grain, allowing engravers to carve finer lines and thus produce more detailed illustrations. Moreover, as a relief printmaking technique, wood engraving could more easily be combined with letterpress printing than printing from a flat or incised surface, while engraved wood blocks were durable enough to last thousands of prints.[22] With the help of steam printing and stereotyped printing plates, which came into widespread use around the mid-nineteenth century, the British literary market saw "a flood of cheap literature" in the 1850s.[23] Between the 1860s and 1880s, the rise in cheap literature was reflected in a rapidly growing number of accessible science journals, including microscopy periodicals.[24] Many of the new cheap books and periodicals were richly illustrated, with publishers relying on the work of wood engravers to provide them with illustrations. However, as the market for cheap literature became more and more competitive during the second half of the nineteenth century, wood engraving gradually developed into a factory system. Publishers split the production of engravings into tasks which could be distributed among workers, who received less training than previous generations of engravers.[25]

The erosion of prices and increasing competition in the literary market also gave publishers an incentive to reuse illustrations. For instance, engravings were commonly reused in works issued by the same publisher. Especially when they had been made for books which did not sell well, such as small poetry editions, engravings were reused to amortise the cost of their production.[26] But illustrations were also reprinted by other publishers, sometimes after the original engravings had been acquired with the permission of their previous owner. At other

B. Shteir, "'Let Us Examine the Flower': Botany in Women's Magazines, 1800–1830," in *Science Serialized: Representations of the Sciences in Nineteenth-Century Periodicals*, ed. Geoffrey Cantor and Sally Shuttleworth (Cambridge, Mass.: MIT Press, 2004), 17-36; Ann B. Shteir, "Gender and 'Modern' Botany in Victorian England," *Osiris* 12, no. 1 (1997): 29-38.

[21] See William Finley, "Making an Impression: An Assessment of the Role of Print Surfaces within the Technological, Commercial, Intellectual and Cultural Trajectory of Book Illustration, C. 1780-C.1860" (PhD dissertation, University of Sheffield, 2018).

[22] See Finley, "Making an Impression."

[23] Aileen Fyfe, *Steam-Powered Knowledge: William Chambers and the Business of Publishing, 1820-1860* (Chicago: University of Chicago Press, 2012).

[24] See Lightman, "Transformations of Nineteenth-Century Publishing." Likewise, most microscopy periodicals were established between the 1860s and 1880s. See Brock, "Patronage and Publishing."

[25] See Roberto, "Democratising Knowledge and Visualising Progress: Illustrations from Chambers's Encyclopaedia, 1859-1892," 64.

[26] See Finley, "Making an Impression," 83.

times, illustrations were copied by illustrators and re-engraved without the knowledge of the original publisher. Piracy for financial profit was condemned by many, but it was indirectly supported by the ideal of making knowledge accessible to all, which continued to be promoted by learned societies throughout the nineteenth century.[27] Since wood engravings could be produced more cheaply than large, illustrated plates, such as lithographs, and could easily be combined with letterpress printing, prints made from wood engravings were among the most widely reproduced and circulated. As this chapter will show, in microscopy, too, illustrations made from wood engravings were among the most mobile and reached very different audiences, even including readers of fictional texts.

Aileen Fyfe, in her study of the publishing business of William Chambers, reminds us that while the growth of the British literary market was accelerated by new printing techniques, these technological developments were shaped by social, political and economic factors, including increasing literacy rates and the lifting of the "taxes on knowledge."[28] Instead of regarding new technologies as an explanation for the "cheap print revolution," we need to ask why and how these technologies were adopted, and by whom.[29] In a similar vein, this chapter does not conceive of the reproduction of images as just a means to share observations more widely with the help of new printing technologies but considers image reuse integral to scientific observation, investigating why microscopists copied illustrations and how these reproductions shaped their observational practices. Moreover, the chapter contributes to the literature on image reuse by studying not only reproductions made by publishers, but also copies produced by private printers. With the rise of photography, microscopists became interested in chemical methods of reproducing text and illustrations, which facilitated the production of small editions of printed matter in their own homes.

Despite the ubiquity of illustrations in the mid-nineteenth-century mass literature, their producers often remained unknown to their viewers. Illustrators and engravers quite literally shaped what microscopists saw in a printed illustration. Yet even before the decline of engraving in the late nineteenth century, engravers acted as "ghostwriters," as they were expected to transfer an illustrator's work to wood while changing it as little as possible.[30] As Rose Roberto writes, scientific illustrators would usually not garner much attention either, at least in comparison to illustrators of fictional literature, who were more likely to be regarded as

[27] For example, the Royal Society supported reprints of its publications, as long as they respected certain rules of courtesy. See Aileen Fyfe, Julie McDougall-Waters, and Noah Moxham, "Credit, Copyright, and the Circulation of Scientific Knowledge: The Royal Society in the Long Nineteenth Century," *Victorian Periodicals Review* 51, no. 4 (2018): 597-615.
[28] See Fyfe, *Steam-Powered Knowledge*.
[29] Fyfe, *Steam-Powered Knowledge*, 4.
[30] Bethan Stevens has proposed the analogy of ghostwriting to describe the work done by engravers. See Bethan Stevens, "Wood Engraving as Ghostwriting: The Dalziel Brothers, Losing One's Name, and Other Hazards of the Trade," *Textual Practice* 33, no. 4 (2019): 645-677.

artists in their own right.[31] While engravers, as well as illustrators and printers, would at least sign expensive illustrated plates, cheaper woodcuts of microscope specimens were rarely attributed to anyone. Notably, books written and illustrated by female scientific writers were often aimed at children or beginners in microscopy and would feature cheap unsigned wood engravings, making women illustrators even less visible than illustrators employed in a workshop to produce illustrated book plates.[32]

These different levels of (in)visibility need to be considered in assessing the data produced by the two citizen science projects that this dissertation draws on, *Science Gossip* and *Worlds of Wonder*. Both projects promised to make scientific illustrators and engravers more visible, but since the citizen scientists transcribed the names of people who signed illustrations, the results of *Science Gossip* and *Worlds of Wonder* are biased towards professional illustrators and engravers. Still, the two projects have made a substantial contribution to the history of scientific illustration by gathering information about hitherto largely undocumented illustrators, engravers and their work. The data show that illustrations were often made by the author of a book or paper and then passed on to the engraver to prepare them for printing. The visualisation above shows the most frequent collaborators, people working together on the same illustration (Fig. 2.4). The bigger and redder the name, the more often this person appeared as collaborator. Thick red lines connecting people show that they produced many illustrations together. Since the same printers worked with several engravers and illustrators, many of the big red names belong to printing houses (e.g. W. H. McFarlane, McFarlane & Erskine, West, Newman & Co., W. West and F. Huth).

[31] Roberto, "Democratising Knowledge and Visualising Progress: Illustrations from Chambers's Encyclopaedia, 1859-1892," 65.

[32] Women also produced illustrations for their husband's books. For example, Charlotte Mary Slack made the illustrations for her husband's handbook on freshwater microscopy. See Henry James Slack, *Marvels of Pond-Life*.

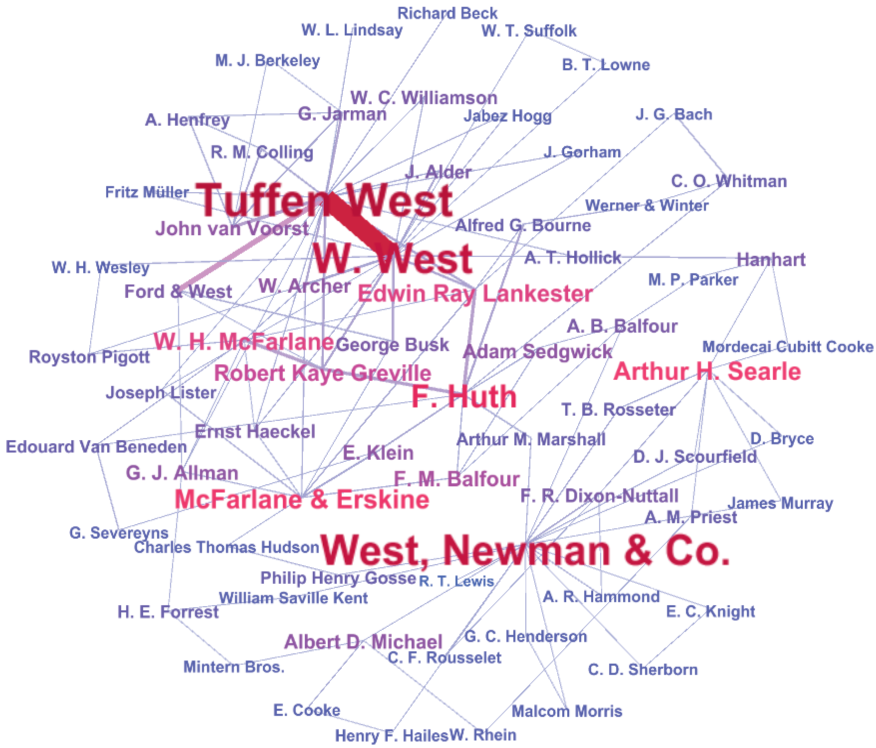

Figure 2.4 Collaborations among microscopy illustrators, engravers and printers, based on data from the *Science Gossip* and *Worlds of Wonder* projects.

Tuffen West, W. West, and West, Newman & Co. are by far the most prominent names in the network. Tuffen West was born in Leeds in 1823, his father a chemist and medical jurist. It was the examination of blood stains in a murder trial that sparked West's interest in microscopy. He trained to become a surgeon, but an explosion in his father's lab put an end to his career, as he lost his hearing. Instead, West went on to work as a scientific illustrator with a younger brother, who was a lithographer and printer based in London.[33] Since West had a younger brother called William, it seems plausible that W. West (later West, Newman & Co.) was the business run by his brother William. This would mean that one family business had

[33] See West's obituary, "The Late Mr. Tuffen West, F.R.M.S," *Journal of the Royal Microscopical Society* 11. Series 2 (1891): 529-532.

an enormous influence on the illustrations readers of microscopy publications saw, and what they expected to see under the microscope.[34]

After joining his brother in London, Tuffen West became one of the most sought-after scientific illustrators in Britain. He illustrated numerous microscopy publications, and also many other works on natural history. West was well connected in scientific circles, being a Fellow of both the Linnaean and the Royal Microscopical Society, and an honorary member of the Zoological and Botanical Society of Vienna, the Tyneside Field Naturalists' Club, and the Leeds Naturalists' Club.[35] Despite West's good connections, his scientific contributions were seldom acknowledged. West's obituary notes that he was mainly recognised as an illustrator although "papers and books were published which really owed quite as much to the man whose name appeared only as artist, as they did to him who assumed the role of author."[36] West used to comment on these rather unfair collaborations saying, "my poverty, but not my will, consents."[37]

The prominence of the printing house W. West was probably due to Tuffen West's good reputation as both an illustrator and a microscopist – the *Journal of the Royal Microscopical Society* called him "unrivalled as a draughtsman and a manipulator."[38] Usually, microscopy publications would be illustrated by experienced microscopists, who had to send their illustrations to an engraver and printer whom they could trust to print the illustrations as intended. The Wests, however, could offer to microscopically observe, illustrate, engrave and print the specimens described by the author, especially if these specimens were everyday objects which could be obtained easily. This kind of vertical integration helped to make the Wests the go-to provider of illustrations for microscopy publishers. Moreover, being based in London, the Wests were in close vicinity of many publishers and microscopy societies. A discussion in the *Northern Microscopist* about the quality of engravings indicates that proximity was indeed a factor in choosing suitable engravers. The journal observed that sending photomicrographs to illustrators did not lead to satisfying results and that illustrators and engravers were best supervised by microscopists.[39] However, the visualisation (Fig. 2.4) shows that London's publishers, for instance the publishers of the *Quarterly Journal of Microscopical Science* (*QJMS*), did also commission engravers and printers from Edinburgh (e.g. W. H. McFarlane, McFarlane & Erskine and F. Huth).

[34] There is a long tradition of family labour in natural history, see, for example, Alix Cooper, "Natural History as a Family Enterprise: Kinship and Inheritance in Eighteenth-Century Science," *Berichte zur Wissenschaftsgeschichte* 44, no. 2 (2021): 211-227.
[35] "The Late Mr. Tuffen West, F.R.M.S," 532.
[36] "The Late Mr. Tuffen West, F.R.M.S," 529.
[37] "The Late Mr. Tuffen West, F.R.M.S," 530.
[38] "The Late Mr. Tuffen West, F.R.M.S," 529.
[39] See "Preparing Illustrations of Microscopical Objects," *The Microscopical News and Northern Microscopist* 3 (1883): 52-54.

Whereas the visualised network of illustrators, engravers and printers above provides a good overview of prominent names in the field, it tells us little about how and why illustrations were produced and (re)used, and how they helped microscopists learn to observe microscope specimens. The next section therefore complements the distant reading of crowdsourced data with a closer examination of the images circulated in the microscopy community. The section follows the illustrations produced by a diverse group of researchers at the bottom left of the visualised network, Philip Henry Gosse, Charles Thomas Hudson, William Saville Kent and H. E. Forrest (Fig. 2.4). These men had a shared interest in freshwater and marine microscopy and therefore observed and illustrated a host of aquatic plants and animals, among them many rotifers. The remainder of this chapter traces rotifer illustrations as they were produced, used and reused in Great Britain and beyond, shedding light on the role of image reuse in observing microscopic life.

In Ponds and Wineglasses: Observing Living Rotifers

Research into rotifers gained traction with naturalists in the mid-nineteenth century, following the publication of Christian Gottfried Ehrenberg's influential work *Die Infusionsthierchen* (1838) and Andrew Pritchard's *A History of Infusoria* (1842). As the two titles indicate, rotifers could not only be found in ponds and puddles but could also be obtained by soaking vegetative matter like decomposing plants in water and waiting for "infusoria" to appear. The term "infusiora" referred to a diverse array of freshwater plants and animals that emerged in such infusions, rotifers being one group among them. Rotifers are primarily found in freshwater, but there are a few saltwater species. They are commonly called wheel animals because they have fast-moving cilia around their mouth, which produce a current to sweep in food and, in motion, look like a turning wheel.

Although Ehrenberg and Pritchard's works were widely read, it took a while for rotifer research to gain enough popularity to warrant publications for beginners in microscopy which were dedicated entirely to rotifers. In 1855, the English naturalist Philip Henry Gosse set out to write a book with the tentative title *The Pond-Raker*, meant to provide a "popular introduction to the Rotifera."[40] Born in Worcester in 1810, Gosse had begun to work as a clerk at a counting house when he was fifteen, but soon left for Canada and the United States, where he tried to make a living as a farmer and private tutor. He returned to England in 1839, and by the 1850s, he had made a name for himself as a scientific writer, drawing on his travels through North America to write natural history books. However, as Gosse's son Ed-

[40] Edmund Gosse, *The Life of Philip Henry Gosse* (London: Kegan Paul, Trench, Trübner & Co., Ltd., 1890), 256.

mund later recalled, "it proved difficult to popularize so abstruse a subject [as rotifers], and *The Pond-Raker* . . . soon quitted his pond and dropped his rake."[41] Gosse never finished his book. Instead, he continued to publish articles dealing with rotifers in various journals, contributing, for example, a whole series of articles on rotifers to the *Popular Science Review.* He also included chapters on rotifers in *Tenby: A Seaside Holiday* (1856) and in his well-received introductory handbook to microscopy, *Evenings at the Microscope* (1859).

The papers and books Gosse published were aimed at very diverse readerships, and he seems to have switched quite effortlessly between different styles of writing. Whereas *Tenby* presented a lively account of Gosse's rambles along the Welsh shore and the plants and animals he encountered, a paper of his published in the *Philosophical Transactions of the Royal Society of London* in the same year was a densely written treatise on the manducatory organs of the rotifera.[42] Gosse made the illustrations, and often even the engravings, for his writings on rotifers himself. With his father an impoverished gentleman trying to make a living off of miniature painting, Gosse had made the drawing of plants and animals a habit when he was only a boy.[43] Gosse's *Tenby* tried to charm its readers with large, coloured plates of rotifers, but it was the simple line drawings in his Royal Society paper and *Evenings at the Microscope* that were soon reproduced in other publications, and whose travels the chapter follows before returning to Gosse's illustrative work.

A search for mentions of Gosse as illustrator in the data collected through *Worlds of Wonder* reveals that both Henry James Slack's *Marvels of Pond-Life* (1861) and Mary Ward's *Microscope Teachings* (1866) copied one of Gosse's illustrations from the 1856 Royal Society paper and credited him as illustrator. *Marvels of Pond-Life* introduced beginners in microscopy to freshwater flora and fauna, each chapter focusing on one month of the year when the reader was most likely to find the specimens described in ponds in the vicinity of London. The book's illustrations had been made by the author's wife, Charlotte Mary Slack. The second edition of the book explained that its

> sketches were made *especially for beginners* and the rule followed, was not to introduce any details that could not be seen at one focus, and with the simplest means: more elaborate representations, though of the highest value to advanced students, are bewildering at the commencement.[44]

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[41] Ibid.
[42] See Philip Henry Gosse, "On the Structure, Functions, and Homologies of the Manducatory Organs in the Class Rotifera," *Philosophical Transactions of the Royal Society of London* 146 (1856): 419-52.
[43] See Ann Thwaite, *Glimpses of the Wonderful: The Life of Philip Henry Gosse, 1810-1888* (London: Faber & Faber, 2002).
[44] Slack, *Marvels of Pond-Life*, v.

One of the challenges of learning how to interpret what was seen through the microscope was that the instrument only provided flat cross-sections of the specimen observed, especially when the depth of field was shallow. The viewer then had to turn these two-dimensional images into a three-dimensional mental image of the specimen. As Schickore writes, teaching students how to translate the flattened image seen through the microscope into an illustration drawn in perspective was a crucial part of their training in microscopy.[45] Slack instead suggested that beginners start by looking at the specimen at one focus only, and this approach was afforded by the illustrations in his book. In the first chapter, Slack explained how to use the microscope in some detail, recommending affordable instruments which could be purchased for three or four pounds and some "whose price is counted in shillings."[46] This shows that *Marvels of Pond-Life* was aimed at microscope users whose instruments might not even have allowed them to observe specimens at different levels of depth.

One illustrated plate in the book, however, combined Charlotte Mary Slack's sketches with a reproduction of one of Gosse's illustrations of the jaw of *Floscularia ornata* from his Royal Society paper (Fig. 2.5, D').[47] The jaw could not be seen "at one focus" in this more analytical drawing but the illustration still featured unchanged in *Marvels of Pond-Life*. Anne Secord has argued that illustrations of botanical specimens which were a pleasure to look at helped to recruit new students into the study of botany.[48] Considering illustrations from the perspective of infrastructure, however, we see that often not the most spectacular illustrations, like lithographs, were reproduced in popular books, but those that were most compatible with a publisher's infrastructure for letterpress printing, such as wood engravings. On the one hand, wood engravings, despite being more detailed than woodcuts, could not express delicate forms and colour, which was regarded as a disadvantage by many contemporary observers. On the other hand, wood engraving afforded the reproduction of diagrammatic line drawings like Gosse's, which, inserted into Slack's book, introduced even beginners to analytical visual descriptions of rotifer anatomy and pointed them to the literature for more advanced learners.

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[45] See Jutta Schickore, "Fixierung mikroskopischer Beobachtungen: Zeichnung, Dauerpräparat, Mikrofotografie," in *Ordnungen der Sichtbarkeit: Fotografie in Wissenschaft, Kunst und Technologie*, ed. Peter Geimer (Frankfurt a. M.: Suhrkamp, 2016), 285-310.
[46] Slack, *Marvels of Pond-Life*, 1.
[47] Slack, *Marvels of Pond-Life*, viii.
[48] See Anne Secord, "Botany on a Plate," *Isis* 93, no. 1 (2002): 28-57.

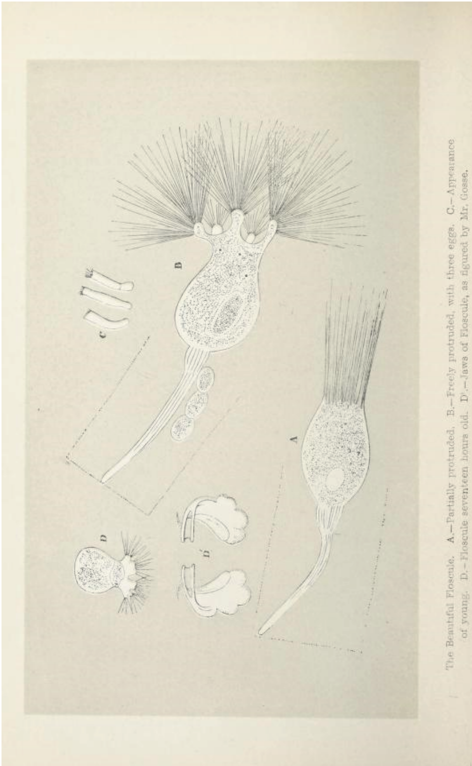

Figure 2.5 Plate in Henry James Slack's *Marvels of Pond-Life*, including an illustration made by Philip Henry Gosse (D'). Image from the Biodiversity Heritage Library. Contributed by the Thomas Fisher Rare Book Library, University of Toronto.

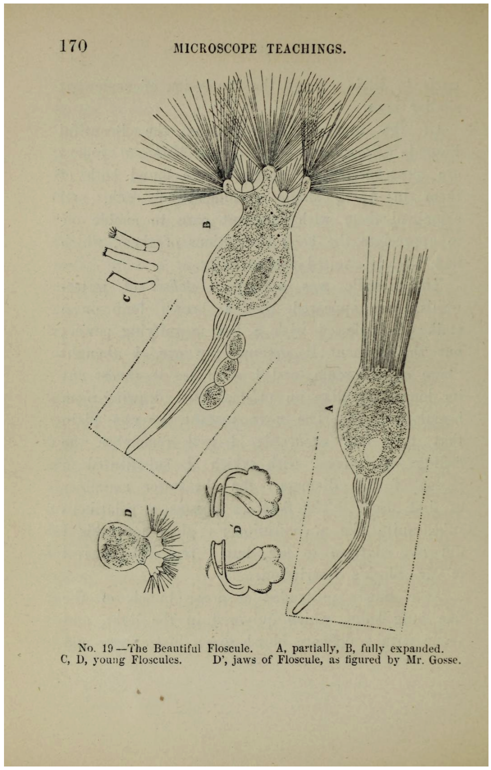

Figure 2.6 Plate reproduced in Mary Ward's *Microscope Teachings*. Image from HathiTrust. Contributed by the University of Illinois at Urbana-Champaign.

In *Marvels of Pond-Life*, Henry James Slack claimed that "verbal descriptions are poor substitutes for the teachings of experience" and that skills in microscopy "must be learned by experiment."[49] Still, his written instructions aimed to train the eye of his readers through figurative language and visual analogies. Slack wrote that some rotifers looked like "a transparent animated soup-plate" or "like the shell of a tortoise."[50] Others had "two apparently elastic bands [which] are bent downwards, till they look like the C springs behind a gentleman's carriage."[51] Yet another rotifer "had her abode in a clear transparent cylinder, like a thin confectioner's jar."[52] Slack's vivid analogies certainly made his book entertaining to read, but they

[49] Slack, *Marvels of Pond-Life*, vi, 19.
[50] Slack, *Marvels of Pond-Life*, 44, 46.
[51] Slack, *Marvels of Pond-Life*, 47.
[52] Slack, *Marvels of Pond-Life*, 56.

also taught aspiring microscopists what to look for when they used the microscope by linking unfamiliar microscopic images to more familiar shapes. The historian Alexander Wragge-Morley has studied early modern rhetorical strategies of "verbal picturing," examining the work of naturalists who "believed it possible to use words to reproduce the experience of vivid picturing, or even the experience of visually encountering things themselves."[53] Developing observational skills in microscopy required experience, but, in a similar way as described by Wragge-Morley, visual imagery could at least facilitate the process of learning how to observe, with Slack's flowery prose affording the acquisition of skill in interpreting what was seen through the microscope. Moreover, Slack's analogies – ranging from tortoise shells to gentleman's carriages and confectioner's jars – show that he assumed his readers to be familiar with middle- and upper-class life and consumer goods, which gives us an indication of the kind of readers targeted by microscopy handbooks in the 1860s.

In 1864, the illustrated plate in Slack's book that contained Gosse's illustration was republished in Mary Ward's *Microscope Teachings*, which still credited Gosse for illustrating the *Floscularia* jaw (Fig. 2.6). Since *Microscope Teachings* was issued by the same publisher as *Marvels of Pond-Life*, it reused the engraving made by Charlotte Mary Slack. Ward's *Microscope Teachings*, as well as her other works on microscopy, presented its microscopy illustrations as resulting from observations made in Ward's very own way. Mary Ward, born into an Anglo-Irish family at Ballylin in 1827, was geographically at the margins of the British scientific community and, as a woman, did not receive a formal scientific education.[54] However, her parents encouraged her in her studies of natural history. After receiving a microscope from her father when she was eighteen years old, Ward began to dedicate much of her time to microscopy, describing and illustrating her observations. She profited from the scientific network of her cousin, the astronomer William Parsons, who brought her in contact with some of the most eminent scientists of her time. From a young age, Ward passed her descriptions and illustrations of microscope specimens on to friends and family. Later, she revised and published her studies in microscopy, with *Microscope Teachings* being the most successful among her publications.[55]

[53] Alexander Wragge-Morley, *Aesthetic Science: Representing Nature in the Royal Society of London, 1650-1720* (Chicago: University of Chicago Press, 2020), 107-108.
[54] The biographical information on Ward provided in this chapter is based on Owen G. Harry, "The Hon. Mrs Ward (1827-1869). Artist, Naturalist, Astronomer and Ireland's First Lady of the Microscope," *The Irish Naturalists' Journal* 21, no. 5 (1984): 193-200.
[55] The book first appeared in 1857 *as Sketches with the Microscope*. In 1858, a second edition was published as *The World of Wonders as Revealed by the Microscope* and in 1864 the title was changed to *Microscope Teachings*. Overall, at least seven editions were published.

Microscope Teachings combined an introductory manual for the use of the microscope with descriptions of the specimens observed and instructions on how to obtain and prepare them. Unlike Ward's earlier publication *The World of Wonders as Revealed by the Microscope* (1858), which introduced readers to microscopy who did not have access to microscopes, its later revised version *Microscope Teachings* was meant to "unite the provinces of the Guide Book and the Panorama" by adding more technical chapters to the book, which contained illustrations of microscopes and other technical equipment.[56] In order to help her readers develop skills in handling the microscope, Ward walked them through every step of unpacking a microscope as they would receive it from an optician, identifying its various parts, assembling the instrument and putting it to use for the first time. Ward also carefully explained how to illuminate a specimen, "a great and important part of the microscopist's craft."[57]

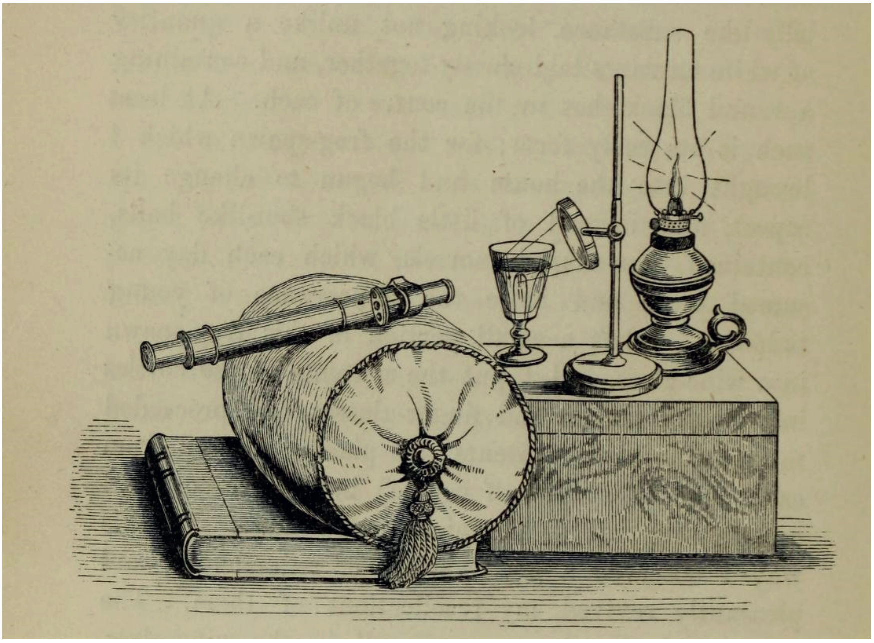

Figure 2.7 Illustration in Mary Ward's *Microscope Teachings*, showing viewers how to observe rotifers in a wineglass. Image from the Biodiversity Heritage Library. Contributed by the Wellesley College Library.

[56] Mary Ward, *Microscope Teachings: Descriptions of Various Objects of Especial Interest and Beauty Adapted for Microscopic Observation* (London: Groombridge and Sons, 1866), viii.
[57] Ward, *Microscope Teachings*, 13.

Ward's book presented microscopy as a domestic, sometimes maternal affair, instructing its readers on how to construct a microscope objective for children and observe freshwater animals kept in a wineglass.[58] Graeme Gooday has argued that the books written by British popularisers of microscopy like Gosse and Ward aimed at disciplining their readers, advising them to confine their scientific pursuits to their own homes.[59] Although Gooday provides a rigorous discourse analysis of indoor science in the late nineteenth century, his article brushes aside the individual agency and resourcefulness of many microscopists working from their homes. Ward provided her readers with an illustration that showed how she "removed the microscope tube from the stand, and mounted it . . . upon a cushion raised on a large book, so that [she] could look as through a telescope into the wine-glass" (Fig. 2.7).[60] Her plan "answered exceedingly well."[61] Ward often ingeniously tinkered with and repurposed household items to make observations, and through both her writing and illustrations she encouraged her readers to do the same.[62]

Gosse may have aimed at "inculcating [his readers] into a moral and orderly appreciation of 'Nature,'" as stated by Gooday, but he had little control over how his illustrations were reused and adapted to someone else's observational practice.[63] By reproducing Gosse's observation of a rotifer's manducatory organ in the context of domestic microscopy which relied on repurposed household items, Ward's *Microscope Teachings* drew on Gosse's knowledge of rotifers but linked his illustration to different observational practices. Building on Johanna Drucker's work, the historian of art and literature Emilie Sitzia has argued that book illustrations "have the potential to simultaneously display existing knowledge – for example, by representing a key narrative moment in the story – and to create new knowledge – such as an alternative parallel narrative or to display a character not described in the text."[64] Sitzia's understanding of visual knowledge production in fictional books seems applicable to the reproduction of microscopy illustrations, too, as reprints of illustrations that appeared in handbooks like Ward's both reproduced previous knowledge of rotifers and, being combined with different images

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[58] Ward thus continued to draw on what Lightman has called the "'familiar fomat', a fictional literary format that used letters, dialogues, and conversations, customarily situated in a domestic setting." Bernard Lightman, *Victorian Popularizers of Science: Designing Nature for New Audiences* (University of Chicago Press, 2009), 21.
[59] See Gooday, "'Nature' in the Laboratory."
[60] Ward, *Microscope Teachings*, 142. Another illustration included in an earlier article written by Mary Ward for the *Intellectual Observer* shows larvae inside a wineglass. Mary Ward, "A Windfall for the Microscope," *The Intellectual Observer: Review of Natural History, Microscopic Research, and Recreative Science* 5 (1864): 13-17.
[61] Ward, *Microscope Teachings*, 142.
[62] Harry writes that Ward also seems to have made microscope slides out of glass shreds. Harry, "The Hon. Mrs Ward."
[63] Gooday, "'Nature' in the Laboratory," 320.
[64] Emilie Sitzia, *"Illustration Is Everyone's Mother Tongue": The Role of Illustration in Individual Identity Formation*, Inaugural Lecture (No. 595), (Amsterdam, Netherlands: University of Amsterdam, 4 July, 2018), 6.

and written instructions, suggested new ways of obtaining it to their viewers. Reproducing microscopy illustrations also made it possible for microscopists at the margins of the scientific community, like women observing specimens at home, to draw themselves into a virtual community of reader-viewers, presenting their own observational practice as a legitimate way of acquiring knowledge about rotifers.

Whereas Gosse's first attempt at publishing an introduction to rotifers for beginners had been fruitless, another effort of his begun in the late 1870s proved more successful. In 1879, Edwin Ray Lankester, zoology professor at University College London and himself an avid microscopy illustrator, advised Gosse to join forces with Charles Thomas Hudson, a science schoolteacher in Bristol.[65] Hudson had researched rotifers at least since the mid-1860s. The most marked result of the ensuing collaboration between Gosse and Hudson was the publication of *The Rotifera* in 1886, which would become a standard work on rotifers and whose illustrations were circulated widely. In the years leading up to the publication of *The Rotifera*, Gosse and Hudson produced several hundred illustrations of rotifers for their book, sometimes reusing visual elements of their earlier illustrated plates. In *The Rotifera,* Gosse and Hudson tried to redefine the field of rotifer study, making a case for observing rotifers in their living state and recording their morphological changes over time.

In *A Naturalist's Sojourn in Jamaica* (1851), Gosse had already declared natural history "a science of dead things; a *necrology"* that should be replaced with "*zoology*, i. e. the science of *living* creatures."[66] Gosse's dedication to the study of living organisms shaped his observational and drawing practices. He dated and signed the many rotifer sketches he produced for *The Rotifera* with "P.H.G. ad nat" and in the book itself, both authors asserted that all illustrations were "drawn from life." Framing these illustrations as drawn from life and emphasizing the morphological development of rotifers in them served the rhetorical purpose of promoting a turn towards zoology (Fig. 2.8). Making a case for the study of living creatures allowed Gosse and Hudson to fashion themselves as field workers who experienced nature first-hand, and thus distinguish themselves from their metropolitan competitors who allegedly worked with collections rather than living specimens.[67]

[65] Edmund Gosse, *Life of Philip Henry Gosse*, 318.
[66] Philip Henry Gosse, *A Naturalist's Sojourn in Jamaica* (London: Longman, Brown, Green, and Longmans, 1851), v-vii. See also Gooday, "'Nature' in the Laboratory," 312.
[67] See Gooday, "'Nature' in the Laboratory."

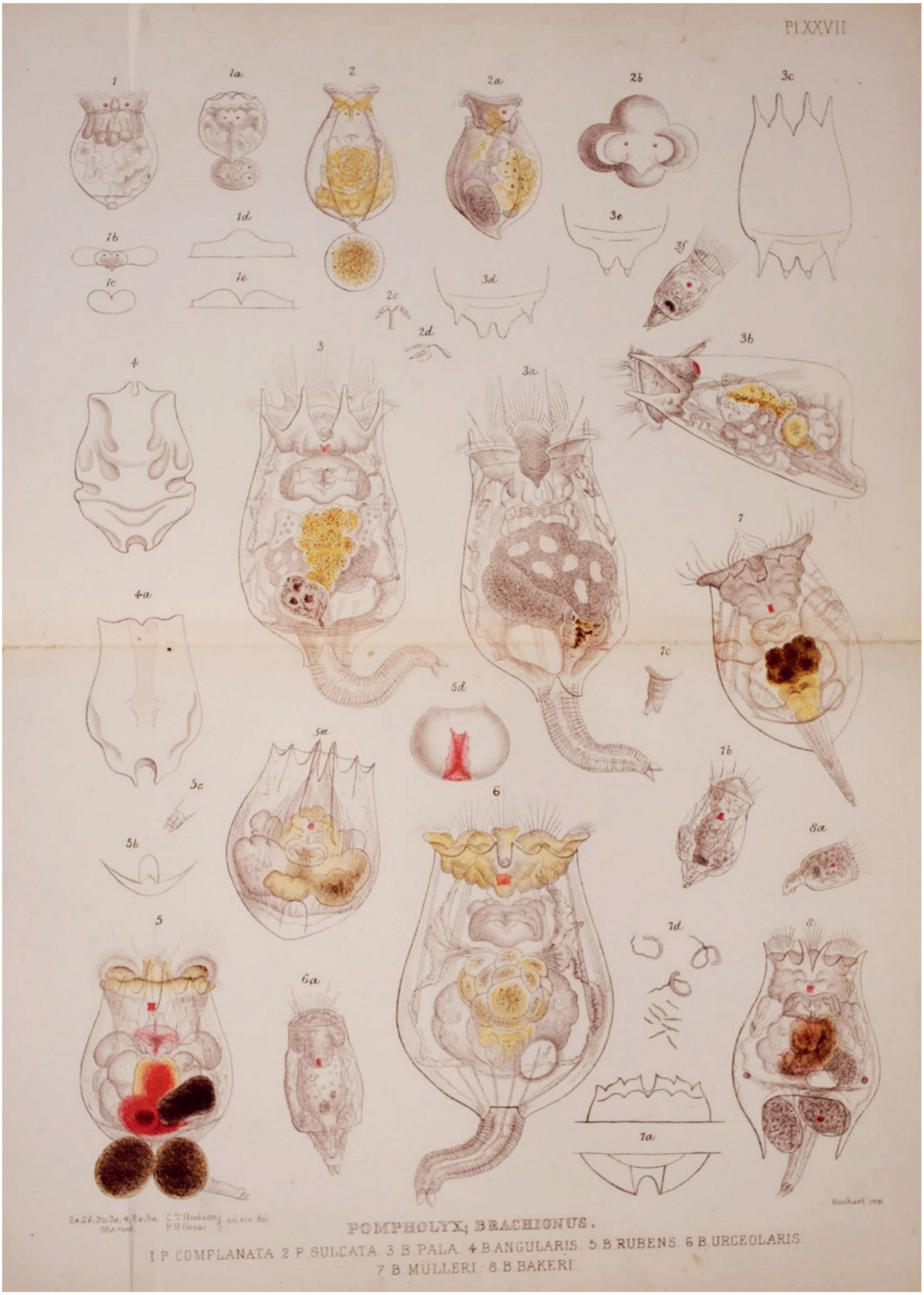

Figure 2.8 Plate from *The Rotifera*, illustrating two genera of rotifers (*Pompholyx, Brachionus*) and their developmental stages. Hudson, C. T., & Gosse, P. H. (1886/1889). *The Rotifera; or Wheel-Animalcules*. London: Longmans, Green, and Co. Plate XXVII. Image from the Biodiversity Heritage Library. Contributed by the Smithsonian Libraries.

Figure 2.9 Illustrated plate of *Floscularia* rotifers, including *Floscularia hoodii*, in *The Rotifera*. Image from the Biodiversity Heritage Library. Contributed by the Smithsonian Libraries.

Figure 2.10 Backlit transparency of *Floscularia hoodii* by Hudson. Image courtesy of Robin Wootton. The image was first published by the Devonshire Association for the Advancement of Science, Literature and Art, https://devonassoc.org.uk/the-hudson-transparencies/.

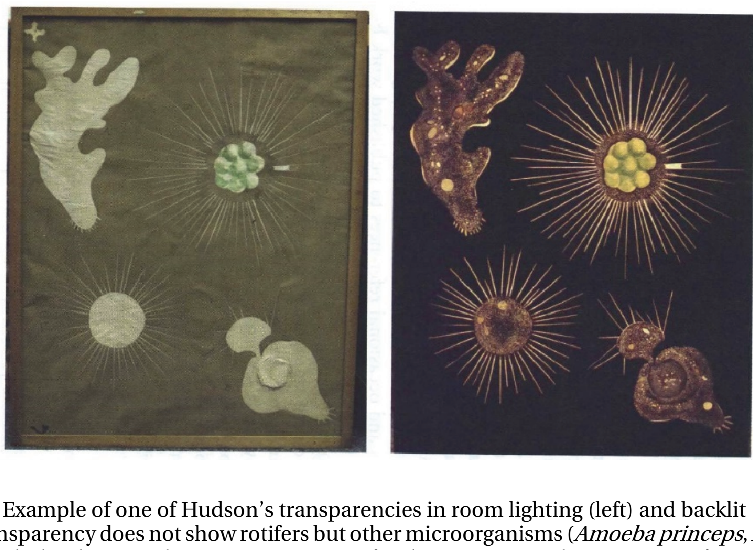

Figure 2.11 Example of one of Hudson's transparencies in room lighting (left) and backlit (right). Note that this transparency does not show rotifers but other microorganisms (*Amoeba princeps*, *Actinophrys sol*, and *Raphidiophrys viridis)*. Image courtesy of Robin Wootton. The image was first published in Wootton, R. (2011). "The Hudson Transparencies. A Set of Remarkable Visual Aids by a Distinguished Victorian Microscopist." *Report and Transactions of the Devonshire Association for the Advancement of Science, Literature and Art*, 143, 61-90.

Following the publication of *The Rotifera*, Hudson decided to turn some of the rotifer illustrations published in the book into visual teaching aids that he could use for scientific lectures (Fig. 2.9, 2.10 and 2.11).[68] Although Hudson seems to have retired from his work as a schoolteacher in 1881, he continued lecturing on rotifers, for example at the meetings of the RMS, using backlit transparencies to illustrate his talks. As the *Journal of the Royal Microscopical Society* recalled in Hudson's obituary, "the outlines of the objects [the microscope specimens] were indicated by means of dots and lines, cut out of a large brown paper screen, the perforations when necessary being covered in with colored transparencies. When illuminated from behind, a dark-ground effect was produced, which was most effective and elegant" (Fig. 2.11).[69] The effect of Hudson's transparencies shown in a dark room must have been dramatic indeed (Fig. 2.10 and 2.11). Hudson considered it essential to present such spectacular views of microscopic creatures to students of natural history, which is in line with Anne Secord's observation that pleasure was crucial in drawing practitioners to botany.[70] In his annual speech as president of the RMS in 1890, Hudson declared that he was convinced that natural history should give its practitioners "a thrill of pleasure."[71]

Throughout his presidential address of 1890, Hudson discouraged his listeners from becoming engrossed in the classification of dead plants and animals captured on permanent slides and instead suggested to observe them in their living state. He explained that the ideal natural history book "should be written with the earnest desire of so interesting the reader in the subject, that he should fling it aside and rush off to find the animals themselves."[72] Hudson's lavish illustrations were closely tied to his and Gosse's understanding of natural history as a science of living creatures. As captivating as Hudson's transparencies were, he felt that they served their purpose best when they were eventually flung aside by the curious researcher to venture into the field to collect living rotifers. Showing illuminated specimens on a dark background, Hudson's transparencies imitated dark-field microscopy, a technique where light is directed at a specimen in such a way that it appears bright against a black background (Fig. 2.10). Dark-field microscopy helps to make transparent, low-contrast specimens more visible, especially when staining them is not an option, for example when the specimen is supposed to be observed alive. Hudson's transparencies, therefore, were not just a visual spectacle

[68] See Robin Wootton, "The Hudson Transparencies. A Set of Remarkable Visual Aids by a Distinguished Victorian Microscopist," *Report and Transactions of the Devonshire Association for the Advancement of Science, Literature and Art* 143 (2011): 61-90.
[69] "Obituary. Charles Thomas Hudson, M.A. Ll.D. F.R.S. Hon. F.R.M.S. 1828-1903," *Journal of the Royal Microscopical Society* (1904): 48-49.
[70] See Secord, "Botany on a Plate."
[71] Charles Thomas Hudson, "The President's Address. On Some Needless Difficulties in the Study of Natural History," *Journal of the Royal Microscopical Society* (1890): 132.
[72] Hudson, "The President's Address," 135.

but, at least to viewers with some experience in microscopy, suggested that rotifers should best be observed with dark-field lighting – and alive.

Perhaps ironically, Gosse and Hudson's professed turn towards studying zoology and living microscopic animals instead of collections of permanent slides was supported by growing infrastructures for supplying metropolitan researchers, as well as school and university students, with living microscope specimens from the countryside. From the late 1870s, instead of venturing into the field to look for rotifers, students and researchers could simply order living microscope specimens by mail. As the following section shows, emerging natural history businesses, helped by the sprawling British postal system and an ever-denser railway network, circulated both living microscope specimens and illustrations of them, and at the same time influenced how they were observed.

"Working Images" and Autographic Printing

In 1878, the Birmingham microscopist Thomas Bolton, formerly the manager of an iron works, established a "Microscopist's and Naturalist's Studio."[73] Bolton's aim was to provide microscopists with all sorts of technical equipment, as well as living microscope specimens, mainly freshwater plants and animals. Based in Birmingham, Bolton's studio was particularly well placed to supply both London's microscopists and those living in the North with material. Bolton exhibited his specimens at various microscopy society meetings in Birmingham and beyond. He also established a postal subscription service to distribute freshwater plants and animals once a week.[74] Each specimen was put in a water-filled glass tube and sent to microscopists through the post. Bolton's preparations travelled a great distance. They were sent to Paris, where they would then be distributed by Jules Pelletan, a French physician and editor of the *Journal de Micrographie*, and they were later advertised in the *American Monthly Microscopical Journal*.[75]

Thomas Bolton's business reflected a wider trend of commercialisation in the trade of natural history objects in the second half of the nineteenth century, fuelled by colonial expansion, the rise of formal education in the natural sciences, and growing middle-class interest in collecting and classifying natural history objects.[76] Natural history dealers and craftspeople, like taxidermists, wax modellers

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[73] Brian Bracegirdle, *Microscopical Mounts and Mounters* (London: Quekett Microscopical Club, 1998), 15.
[74] For a study of the role of the penny post in exchanging entomological specimens, see Chapter Two in Matthew R. Wale, "'The Sympathy of a Crowd': Periodicals and the Practices of Natural History in Nineteenth-Century Britain" (PhD dissertation, University of Leicester, 2018).
[75] See "Science-Gossip," *The American Monthly Microscopical Journal* 19 (1898): 14-16; Jules Pelletan, "Revue," *Journal de Micrographie* 5 (1881): 351-357.
[76] See Coote et al., "When Commerce, Science, and Leisure Collaborated."

and microscope slide makers, were essential in supplying museums and other educational scientific institutions with objects.[77] Moreover, the introduction of the Uniform Penny Post in 1840 had facilitated the exchange of light-weight objects among British scientific practitioners, such as insects and other microscope specimens.[78] Many microscopists established “microscopical institutes,” microscopy supply businesses, which produced a large number of microscope slides and instruments and sent them to scientists and scientific institutions all over the world.[79] In the case of Bolton’s studio, customers were provided with both specimens and instructions on how to observe them – every glass tube sent out was accompanied by a “flyleaf”, as Bolton called it, consisting of a short description and illustration of the specimen in the tube.

The flyleaf issued by Bolton on June 4th, 1880, was an extract from an article on a species of rotifer, the crown animalcule, which Gosse had written for the *Popular Science Review* in 1862.[80] The illustration Gosse had made for the article offered the readers of the journal spectacular microscopic landscapes, a true “world of wonder” (Fig. 2.12).[81] Lightman has argued that such extravagant illustrations were often produced with a view to instilling reverence for God’s creation in their viewers.[82] While Gosse was indeed a devout Christian, visual microscopic landscapes like his were also produced for more pragmatic reasons. As Mary Ward pointed out in her *Microscope Teachings*, microscope panoramas sometimes served as a substitute for the actual gaze through the microscope at a time when not everyone could afford to buy the instrument.[83] In any case, like Hudson’s transparencies, Gosse’s illustrations in the *Popular Science Review* were supposed to be marvelled at, rather than directly compared with what was seen under the microscope. In contrast to his illustration, Gosse’s text catered to a specialist audience, providing lengthy and detailed descriptions of rotifer species. Maybe surprisingly, Gosse’s rather inaccessible text seems to have travelled further than his illustration, since Bolton’s 1880 flyleaf only reproduced Gosse’s written observations. From a methodological perspective, this shows that by tracing reproductions of

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[77] See Nick Hopwood, *Embryos in Wax: Models from the Ziegler Studio* (Cambridge and Bern: Whipple Museum of the History of Science, University of Cambridge, and the Institute of the History of Medicine, University of Bern, 2002); Susan Leigh Star, "Craft vs. Commodity, Mess vs. Transcendence: How the Right Tool Became the Wrong One in the Case of Taxidermy and Natural History," in *The Right Tools for the Job: At Work in Twentieth-Century Life Sciences*, ed. Adele E. Clarke and Joan H. Fujimura (Princeton, NJ: Princeton University Press, 1992), 257-286.
[78] Wale, “'The Sympathy of a Crowd',” 96.
[79] See Hintzsche, "Schweizer ‘Mikroskopische Institute’."
[80] For a comprehensive analysis of the contents of the *Popular Science Review*, see Ruth Barton, "Just before Nature: The Purposes of Science and the Purposes of Popularization in Some English Popular Science Journals of the 1860s," *Annals of Science* 55, no. 1 (1998): 1-33.
[81] Philip Henry Gosse, *Evenings at the Microscope; or Researches among the Minuter Organs and Forms of Animal Life* (New York: D. Appleton, 1860), 3.
[82] See Lightman, "Visual Theology."
[83] According to Ward, however, this had changed by the time her *Microscope Teachings* (1866) appeared, which offered technical advice for using microscopes rather than microscope panoramas.

text in addition to illustrations, we can see where illustrations did not travel, and investigate why they might have been replaced.

Figure 2.12 Philip Henry Gosse's illustration of the crown animalcule (a and b) and other builder animalcules in the *Popular Science Review* (1862), 1, Plate XXVI. Image from the Biodiversity Heritage Library. Contributed by the Natural History Museum Library, London.

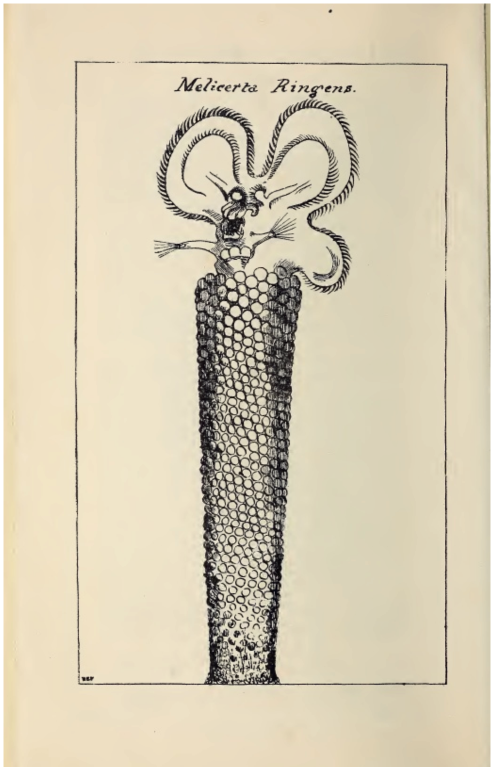

Figure 2.13 H. E. Forrest's illustration of a crown animalcule in Thomas Bolton's flyleaves, 1880. Bolton, T. (1879-1882). *Hints on the Preservation of Living Objects and Their Examination Under the Microscope*. Birmingham: Herald Printing Offices. Image from the Biodiversity Heritage Library. Contributed by the University of Toronto Thomas Fisher Rare Book Library.

In Bolton's flyleaf, Gosse's illustration was replaced by one made by H. E. Forrest, another Birmingham-based microscopist, who illustrated many of Bolton's flyleaves (Fig. 2.13). Forrest's illustration shows a single crown animalcule instead of a whole landscape of microscopic animals. This was the regular format of Bolton's flyleaves: an extract from a book or journal, often adapted according to Bolton's own methods and observations, combined with an illustration of a single specimen. Bolton's lists of subscribers show that many of his specimens were sent to science educators and educational institutions, including university professors, schoolteachers, museums, and colleges.[84] Bolton's flyers were evidently meant to teach students of zoology and botany how to observe and describe microorganisms. Considering that Gosse's rich illustrations in the *Popular Science Review* functioned as a replacement of, rather than a complement to, an observation made through the microscope, this may have been a reason to use Forrest's more descriptive illustration of a single crown animalcule instead. Whereas in Gosse's panoramic view the rotifer was one among many microorganisms attached to a piece of weed floating through water (Fig. 2.12), Forrest's illustration, like Bolton's glass tube, extracted the rotifer from its outdoors environment. Looking somewhat like late-nineteenth-century trading cards, Bolton's flyleaves presented living rotifers as collectibles, to be ordered on demand and examined at ease under the microscope (Fig. 2.13).[85]

Bolton's flyleaves explained to his subscribers how to locate and extract the specimen from the glass tube they received, which features to look for, how to distinguish the specimen from similar species, as well as how to keep it alive and observe it in its most "natural" state.[86] In 1879, Bolton published a series of letters in the *English Mechanic*, in which he gave some general "Hints on the Preservation of Living Objects, and Their Examination Under the Microscope," after he had been asked for more extensive instructions by his subscribers.[87] Bolton's instructions threaded a fine line between keeping a microscopic animal alive and restricting its movement so it could be observed without difficulty, for example by pouring the water containing the specimen on a cotton ball, which the animal would get tangled up in. Also, in keeping with Bolton's educational mission, his instructions were aimed at making well-known features visible to observers who were unfamiliar with microscopic plants and animals. Bolton noted, for example, that rotifers raised in captivity were more transparent than their pond-dwelling relatives, which rendered their internal organs more visible.

Bolton's illustrator Forrest explained in the flyleaves that making a detailed drawing of a microscope specimen was a way of observing it closely. On finding a water flea in a glass tube Bolton had sent him in 1879, Forrest "saw . . . at the first glance that it was a form new to [him], and forthwith set about drawing it. That

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[84] These lists are not exhaustive since they only include subscribers whom Bolton deemed important to mention. However, they clearly show the educational role Bolton ascribed to his agency. Thomas Bolton, *Hints on the Preservation of Living Objects and Their Examination under the Microscope* (Birmingham: Herald Printing Offices, 1879-1882).

[85] On the history of nineteenth-century trading cards, see Jennifer M. Black, "Exchange Cards: Advertising, Album Making, and the Commodification of Sentiment in the Gilded Age," *Winterthur Portfolio* 51, no. 1 (2017): 1-53; Judith Blume, "The Rise of the Trading Card: Collecting the World before World War I," in *The World of Children: Foreign Cultures in Nineteenth-Century German Education and Entertainment*, ed. Simone Lässig and Andreas Weiß (New York and Oxford: Berghahn Books, 2020), 228-251.

[86] Bolton, *Hints on the Preservation of Living Objects*, 3.

[87] See Thomas Bolton, "Hints on the Preservation of Living Objects, and Their Examination under the Microscope," *English Mechanic and World of Science* 30 (1879): 262-263.

done, the next thing was to find out its name."[88] Drawing the water flea evidently preceded its classification. Forrest's drawings, therefore, were what Omar Nasim has called "working images," preliminary scientific drawings which precede the published illustration, and which are themselves a mode of observation, or a way of probing what is seen with the eye.[89] Nasim defines "working images" as messy, private sketches that are part of the practice of scientific observation and that only later result in stabilized published illustrations, or "immutable mobiles."[90]

While this chapter embraces Nasim's proposal of acknowledging the drawing of illustrations as an observational practice that depended on the hand as much as the mind, it questions his distinction between volatile sketches and allegedly immutable, published illustrations. As this chapter has shown, the late-nineteenth-century print trade thrived on reproducing texts and illustrations, making it difficult to determine what counts as the final published version of a sketch. Even after its first publication, a drawing would often be copied, adapted, and republished, making these illustrations hardly less mutable than the initial drawing. Moreover, some of the sources that this chapter draws on, for example Bolton's flyleaves, which were only later bound and formally published, moved in a liminal space between the published and unpublished. Recognising the instability and long trajectory of published scientific illustrations in the late nineteenth century broadens the scope of practitioners and materials involved in the making of these illustrations. A scientific illustration was produced not only by the people and objects involved in its first publication, but also by those using and adapting it afterwards, copying and republishing it, or by adding the illustration to a collection of journal clippings or a scrapbook.[91] If we take up Nasim's suggestion of regarding working images as a mode of scientific observation, then the multiple reproductions of microscopy illustrations – by hand and through print – show that scientific observation was, in fact, a drawn-out process that continued even without the microscopic object initially observed.

Forrest was one of two illustrators commissioned by Bolton to illustrate his flyleaves between 1879 and 1882.[92] The other was William Saville Kent, a zoologist educated at King's College and the Royal School of Mines under Thomas Huxley. Saville Kent had worked at the British Museum and at the public aquariums in Brighton and Manchester. When his sketches appeared in Bolton's flyleaves, he

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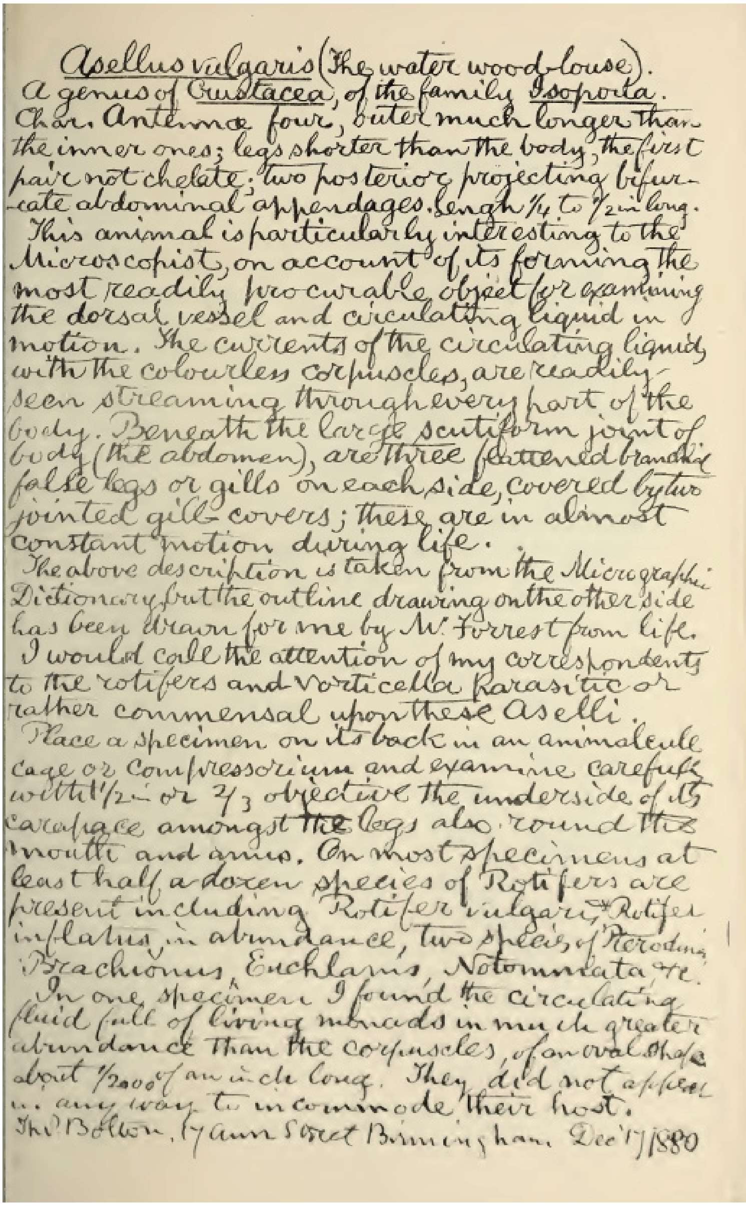
[88] Bolton, *Hints on the Preservation of Living Objects*.
[89] Nasim's "working images" build on Alpers's notion of "picturing" as opposed to "pictures," the finished, stabilised products of picturing an image. Nasim, *Observing by Hand*. Svetlana Alpers, *The Art of Describing: Dutch Art in the Seventeenth Century* (Chicago: University of Chicago Press, 1983).
[90] Nasim draws on Bruno Latour's concept of immutable mobiles in "Drawing Things Together," in *Representation in Scientific Practice*, ed. Michael Lynch and Steve Woolgar (Cambridge, MA: MIT Press, 1990): 19-68.
[91] Roberto, "Democratising Knowledge and Visualising Progress: Illustrations from Chambers's Encyclopaedia, 1859-1892." See also Ellen Gruber Garvey, *Writing with Scissors: American Scrapbooks from the Civil War to the Harlem Renaissance* (Oxford and New York: Oxford University Press, 2012).
[92] The flyleaves issued between 1879 and 1882 are the only ones I could find.

was simultaneously working on *A Manual of the Infusoria* (1880-1882), a three-volume work dealing with both marine and freshwater microorganisms. In the preface to the first volume, Saville Kent thanked Bolton for providing him with the specimens described and pictured in the manual. There are slight differences between Saville Kent's illustrations in the flyleaves and in the manual, which may indicate that Saville Kent, like Forrest, drew specimens for Bolton's flyleaves in order to observe them better, before making the illustrations that would be published in the manual.

Saville Kent and Forrest's illustrations, as well as their accompanying texts, were reproduced through autographic printing, a novel printing technique invented by the Birmingham photographer A. Pumphrey, which allowed Bolton to duplicate his flyers without the help of an engraver or printer. Instead, drawings were reproduced through a chemical process. A drawing was laid on a slab of slate coated with a kind of gelatine and a solution of bichromate of potash. The drawing ink reacted with the bichromate of potash and hardened the gelatine along the lines of the drawing, which could then be coated with ink and printed. *The Midland Naturalist* reported on a demonstration of the process at a meeting of the Birmingham Natural History and Microscopical Society and invited its readers to visit Bolton's studio and see the process first-hand.[93]

Through autographic printing, microscopists like Bolton could duplicate handwritten texts and illustrations at home without much effort. Having promised his subscribers to provide them with *living* specimens, Bolton had to describe, illustrate, and dispatch his specimens fast, which impacted his illustrations. The *Journal of Science* noticed that some of Bolton's illustrations "were roughly printed . . . and dispatched hastily with some specimen unable to bear delay," but overall, the journal considered the flyleaves "extremely well executed" and "a useful collection for reference."[94] The historian Mareike Vennen, in her cultural history of the aquarium, writes that the logistics of shipping living aquatic animals shaped what was known about them. The challenge of keeping these animals alive during transit spurred research into their behaviour and living conditions.[95] In a similar way, Bolton's promise to deliver living specimens impacted how they were observed by his clients. Prioritising a speedy delivery limited the time Bolton and his illustrators could spend on making and duplicating a sketch, which shaped the illustration his subscribers received and what they expected to see when they observed rotifers and other specimens under the microscope.

[93] See William B. Grove, "Autographic Printing," *The Midland Naturalist* 1 (1878): 132-133.
[94] "Analyses of Books," *Journal of Science* 19 (1882): 685.
[95] See Vennen, *Das Aquarium*.



Asellus vulgaris (The water wood-louse).
A genus of Crustacea, of the family Isopoda.
Char. Antennæ four, outer much longer than the inner ones; legs shorter than the body, the first pair not chelate; two posterior projecting bifur-cate abdominal appendages. Length 1/4 to 1/2 in long.
This animal is particularly interesting to the Microscopist, on account of its forming the most readily procurable object for examining the dorsal vessel and circulating liquid in motion. The currents of the circulating liquid, with the colourless corpuscles, are readily seen streaming through every part of the body. Beneath the large scutiform joint of body (the abdomen), are three flattened branchial false legs or gills on each side, covered by two jointed gill-covers; these are in almost constant motion during life.
The above description is taken from the Micrographic Dictionary, but the outline drawing on the other side has been drawn for me by Mr Forrest from life.
I would call the attention of my correspondents to the rotifers and Vorticella parasitic or rather commensal upon these Aselli.
Place a specimen on its back in an animalcule cage or compressorium and examine carefully with 1/2 in or 2/3 objective the underside of its carapace amongst ~~the~~ legs also round the mouth and anus. On most specimens at least half a dozen species of Rotifers are present including Rotifer vulgaris, Rotifer inflatus, in abundance, two species of Pterodina, Brachionus, Euchlanis, Notommata &c.
In one specimen I found the circulating fluid full of living monads in much greater abundance than the corpuscles, of an oval shape about 1/2000 of an inch long. They did not appear in any way to incommode their host.
Thos Bolton, 17 Ann Street Birmingham Dec 17/1880

Figure 2.14 One of Thomas Bolton's handwritten descriptions, duplicated through autographic printing, 1880. Bolton, T. (1879-1882). *Hints on the Preservation of Living Objects and Their Examination Under the Microscope*. Birmingham: Herald Printing Offices. Image from the Biodiversity Heritage Library. Contributed by the University of Toronto Thomas Fisher Rare Book Library.

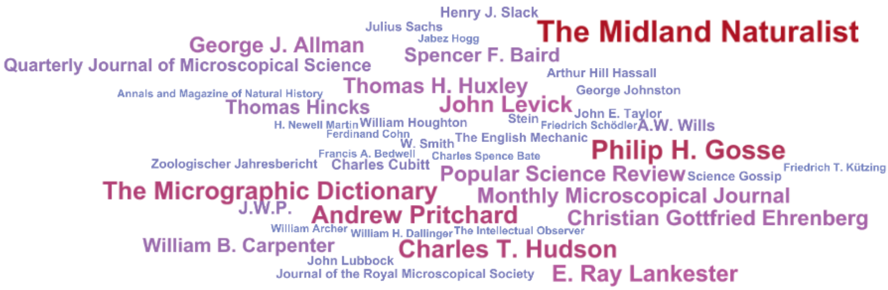


Figure 2.15 People, books and journals frequently mentioned in Bolton's flyleaves (1879–1882), sized and coloured accord-ing to their frequency of occurrence. The word cloud shows Bolton's close connection to *The Midland Naturalist*, as well as Gosse and Hudson.

Bolton's flyleaves gave the impression of being personal correspondence, as the autographic printing kept Bolton's sketchy handwriting intact (Fig. 2.14).[96] Autographic printing made it possible for Bolton to increase his reach among microscopists without sacrificing the benefits of personal correspondence, like short delivery times of specimens and sharing illustrations without interference by a printer or publisher. However, the informality of Bolton's distribution network limited his authority on scientific questions. Although bound and published at intervals, not everyone considered the flyleaves proper scientific publications. For example, Bolton's discovery and description of a new rotifer species in his flyleaves, *Floscularia mutabilis*, remained contested. As the Bulletin of the United States National Museum put it in 1913, this "species has been credited to Hudson, as it is very doubtful whether the description in 'Bolton's flyleaves' can be accepted as publication."[97] Hence, the mode of reproduction – sharing observations with the help of autographic printing instead of having them issued by a publisher – influenced not only the materiality of an illustration, but also how much scientific authority was attributed to the observer.

Many illustrations were especially made for Bolton's flyleaves by Forrest or Saville Kent, whereas others were copied by them from illustrations published elsewhere. Bolton's flyers recombined texts and illustrations taken from various books and journals, mostly acknowledging the work of other authors and illustrators by referring the reader to their publications. Bolton thus introduced aspiring botanists and zoologists to a virtual community of scientific authors and illustrators, occasionally even distributing letters his studio had received from prominent

[96] As the *Journal de Micrographie* observed, Bolton, being "l'homme d'Europe qui écrit le plus mal," decided to hire a scribe around 1881. Pelletan, "Revue." Still, his flyleaves continued to be handwritten.
[97] Harry K. Harring, *Synopsis of the Rotatoria*, Bulletin of the United States National Museum, (Washington, DC: Government Printing Office, 1913), 28.

microscopists. The word cloud above visualises the works and people that were copied or cited most often in the flyleaves, excluding Bolton himself and his two most frequent illustrators, Forrest and Saville Kent, whose names would have overshadowed the rest (Fig. 2.15).

Bolton's scissors-and-paste approach makes it possible for us to reconstruct which works of reference were available to a natural history dealer like him. As the visualisation shows, Bolton's flyleaves copied illustrations and texts from standard works on freshwater microscopy, such as books and articles by Andrew Pritchard, Christian Gottfried Ehrenberg, Philip Henry Gosse and Charles Thomas Hudson. Bolton also drew on more general microscopy publications, like *The Micrographic Dictionary*, the *Monthly Microscopical Journal* and the *Quarterly Journal of Microscopical Science*, as well as a few German authors and periodicals. What may be more surprising is how much the flyleaves relied on *The Midland Naturalist*. Established in 1878, the periodical was "a communication hub for a set of naturalist societies operating in British cities and towns in the triangle between Birmingham, Nottingham and Northampton."[98] *The Midland Naturalist* regularly reported on society activities, including the society excursions during which Bolton and his acquaintances collected the material sent to his subscribers. Specimens found on excursions would be described in *The Midland Naturalist*, and the articles or illustrations either cited or copied by Bolton and his collaborators. This made *The Midland Naturalist* – and natural history societies in the Midlands – a crucial part of Bolton's knowledge infrastructures. It also linked the collecting activities of society members to the research and scientific training of the subscribers who received Bolton's glass tubes. The annual rhythm of country rambles and the places society members went directly affected the flow of microscope specimens Bolton's subscribers received and got to examine under the microscope.

The visualisation (Fig. 2.15) of the most frequent references in the flyleaves also exposes Bolton's connection to two professionalisers of science and science education, Edwin Ray Lankester and his mentor Thomas Huxley. Both were involved in reforming university education, teaching the new discipline of biology through *Anschauung* while tying it closely to their own laboratory research.[99] Bolton often asked Lankester for advice when classifying specimens, which he then acknowledged in his flyleaves, while Lankester was a strong supporter of Bolton's studio. He was one of its earliest subscribers and warmly recommended Bolton's

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[98] Belknap, "Illustrating Natural History," 24.

[99] For closer studies of Lankester and Huxley's educational agenda, see Ruth Barton, "'Men of Science': Language, Identity and Professionalization in the Mid-Victorian Scientific Community." *History of Science* 41, no. 1 (2003): 73-119; Adrian Desmond, "Redefining the X Axis: 'Professionals,' 'Amateurs' and the Making of Mid-Victorian Biology: A Progress Report," *Journal of the History of Biology* 34, no. 1 (2001): 3-50; Joseph Lester, "E. Ray Lankester and the Making of Modern British Biology," ed. Peter J. Bowler, BSHS Monographs (Oxford: British Society for the History of Science, 1995).

service in the *Quarterly Journal of Microscopical Science* in 1879.[100] Since Bolton supplied numerous educators and educational institutions with material, the case of Bolton and his studio demonstrates the importance of taking into account suppliers of teaching materials in researching educational reform, especially since Bolton also provided instructions on how to observe microscope specimens.[101] As Graeme Gooday has argued, "'Nature' was domesticated into the metropolitan parlour and laboratory between the 1850s and 1870s" by reformers of science education who enlisted the microscope "as a trustworthy indoor mediator of 'Nature'."[102] Natural history dealers like Bolton played a major role in the process, turning microscopic creatures into commercial commodities that could be examined by teachers and students without having to venture into the field to collect specimens. His subscription service, including the trading-card flyleaves, turned rotifers into mobile, living collectibles and thus helped to move nature indoors.

Thomas Bolton of the Birmingham studio died in 1887. Yet his agency soon resumed sending specimens to European microscopists and even seems to have extended its business to North American subscribers. European and American journals, like *Hardwicke's Science Gossip* and the *American Monthly Microscopical Journal,* continued to include adverts for Thomas Bolton's living microscope specimens. At the request of a correspondent, *Hardwicke's Science Gossip* confirmed in 1890 that Bolton's sons carried on their father's business, but the journal could not ascertain if the flyleaves were still being issued.[103] A sketchbook dating to 1889, held by the Oxford History of Science Museum and attributed to a "Thomas Bolton," contains a wealth of rotifer illustrations accurately copied from Hudson and Gosse's *The Rotifera*. Apparently, one of Thomas Bolton's sons continued not only his father's business, but also the circulation of Gosse's rotifer illustrations, closely observing and copying them in his private sketchbook.[104] In the hands of Bolton's son, Gosse's illustrations altogether replaced the specimen seen through the microscope, as he taught himself to observe rotifers by copying Gosse's observations, assigning the copied illustrations in his sketchbook the figure and plate numbers corresponding with those in *The Rotifera*. The working images produced by Bolton's son helped him acquire observational skills even though he observed illustrations of microscope specimens that were, in fact, long gone.

[100] See E. Ray Lankester, "Mr. Bolton's Agency for the Supply of Microscopic Organisms," *Quarterly Journal of Microscopical Science* 19 (1879): 492-493.
[101] Laura Newman and Felix Driver have made a similar point regarding museums as suppliers of teaching materials in Laura Newman and Felix Driver, "Kew Gardens and the Emergence of the School Museum in Britain, 1880–1930," *The Historical Journal* 63, no. 5 (2019): 1-27.
[102] Gooday, "'Nature' in the Laboratory," 309.
[103] See "Notices to Correspondents," *Hardwicke's Science Gossip* 26 (1890): 119-120.
[104] Bolton's sons were S. P. Bolton and T. E. Bolton – it seems likely that the latter was named after his father.

Taking Rotifer Illustrations Abroad

In 1879, Edwin Ray Lankester recommended Bolton's service to "[e]very naturalist within a day's post of Birmingham," which at the time meant that Bolton's living specimens could be shipped as far as Paris.[105] And indeed, soon after it was established, Bolton's studio started sending microscope specimens to French subscribers. The *Journal de Micrographie*, edited by the Parisian doctor Jules Pelletan, began to feature Bolton's adverts for "spécimens vivants pour le microscope" as early as May 1878. Moreover, Pelletan turned his editorial office into a depository for Bolton's microscopic plants and animals. He believed that ordering specimens in bulk decreased the risk of them being damaged in the post. After receiving Bolton's microorganisms, Pelletan would transfer them to his own aquariums so microscopists from Paris and its surroundings could come and pick them up at their leisure.[106]

Pelletan's office fulfilled a similar function as Bolton's studio, supplying microscopists with any tools they might wish for, including Pumphrey's autographic printing press in three different sizes.[107] Unlike Bolton, Pelletan was a doctor, editor and science journalist. Bolton depended on local society publications and his autographic printing press to circulate information and advertise his business. Pelletan, on the contrary, could rely on formal publications to make a name for himself but presented autographic printing as an ingenious solution to authors who could not afford to have their illustrations engraved and printed. In July 1878, Pelletan's *Journal de Micrographie* included an illustration of flagellates made by Bolton's illustrator Saville Kent and reproduced through autographic printing. The journal demonstrated to its readers that sharing observations of microscopic creatures was facilitated by the skilled use of printing technologies, which could conveniently be purchased at Pelletan's office. In addition to scientifically describing Kent's flagellates, the journal framed the illustration as an advert for Pumphrey's printing press. Asking its readers to examine the execution of the illustration rather than its pictorial content, the *Journal de Micrographie* proposed a figure-ground shift: in Pelletan's journal, learning to observe microscope specimens entailed the close examination of the printing technologies used to illustrate them and judge

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[105] Lankester, "Mr. Bolton's Agency," 492. In 1881, the South Eastern Railway advertised its 8 1/2 hour connection between London and Paris, and it took trains around three hours to go from Birmingham to London. See South Eastern Railway, "Time Tables of the South Eastern Railway and Steam Packets," (London: McCorquodale & Company Ltd., 1881).

[106] "Comme, d'autre part, les accidents sont plus rares quand les expéditions sont un peu plus considérables, nous avons pensé, afin de permettre à tous nos lecteurs de se procurer des spécimens vivants, à établir au bureau du *Journal de Micrographie*, une sorte de dépôt, que nous enrichirons d'ailleurs du contenu de nos propres aquariums, et où les microscopistes trop éloignés pourront s'approvisionner, lorsqu'il sera peu prudent de s'adresser jusqu'à Birmingham." Jules Pelletan, "Envois de Spécimens vivants pour le Microscope," *Journal de Micrographie* 2 (1878): 279.

[107] See Jules Pelletan, "Laboratoire de Microscopie du Journal de Micrographie," *Journal de Micrographie* 2, no. 10 (1878): 443.

their suitability for reproducing observations. Pelletan's readers were also reminded that Bolton's flyleaves had been produced swiftly and should, therefore, not be considered the pinnacle of autographic printing. If done well, Pelletan explained, autographic prints could be just as detailed as engravings.[108]

Bolton's subscription service was not the only way Gosse and Hudson's rotifer texts and illustrations made it to the European continent. In his *Journal de Micrographie*, Pelletan reviewed Hudson and Gosse's *The Rotifera* immediately after its publication in 1886. Alongside highly technical descriptions of rotifer species, *The Rotifera* continued a style of writing usually associated with works on natural history that targeted hobbyist researchers, offering its readers entertaining accounts of the authors' country rambles. In the introduction, Gosse and Hudson reminisced about a visit to an old pond near Clifton and exclaimed, "if . . . we could shrink into living atoms and plunge under the water, of what a world of wonders should we then form part!"[109] The familiar tone chosen by Gosse and Hudson resonated with Pelletan. In his review, he recommended *The Rotifera* to "*amateurs*" or "*micrographes,*" whose work he considered complementary to the research undertaken by "*microscopistes.*" As Pelletan saw it, the latter group, mainly consisting of emerging bacteriologists, treated the microscope as merely a means to an end, whereas the micrographes' enthusiasm for the microscope did more to improve the instrument.[110]

Despite its rather eclectic style, *The Rotifera* was read by German zoologists, too. Friedrich Blochmann, professor of zoology at Heidelberg University, anticipated in 1886 that the many illustrations in *The Rotifera* would be particularly useful for closing gaps in the research on rotifers.[111] After its publication, *The Rotifera* was extensively cited in the *Zeitschrift für wissenschaftliche Zoologie*, the mouthpiece of zoologists in the German lands since 1848.[112] Many of its illustrations were also reproduced in works on limnological studies undertaken at emerging biological field stations, such as Otto Zacharias' *Die Tier- und Pflanzenwelt des Süßwassers* (1891), and Carl Apstein's *Das Süsswasserplankton: Methode und Resultate der quantitativen Untersuchung* (1896) which propagated a quantitative

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[108] See Jules Pelletan, "Une Nouvelle Presse Autographique," *Journal de Micrographie* 2 (1878): 284-285.

[109] Charles Thomas Hudson and Philip Henry Gosse, *The Rotifera; or Wheel-Animalcules*, 2 vols. (London: Longmans, Green, and Co., 1886/1889), 3.

[110] Jules Pelletan, "Revue," *Journal de Micrographie* 13, no. 8 (1889): 225-30; Jules Pelletan, "Bibliographie," *Journal de Micrographie* 10, no. 2 (1886): 93-99.

[111] "[Zu] hoffen ist, dass das in Aussicht stehende umfangreiche Werk über Räderthiere von Hudson und Gosse einen grossen Theil der noch bestehenden Lücken ausfüllen und vor Allem auch die für viele Arten noch fehlenden ausreichenden Abbildungen bringen wird." Friedrich Blochmann and Oskar Kirchner, *Die mikroskopische Pflanzen- und Thierwelt des Süsswassers*, vol. II. (Braunschweig: Verlag von Gebrüder Haering, 1886), iv.

[112] Lynn K. Nyhart, *Biology Takes Form: Animal Morphology and the German Universities, 1800-1900* (Chicago: University of Chicago Press, 1995).

approach to freshwater research.[113] Notably, Gosse and Hudson's visual and textual rhetoric of presenting themselves as zoologists researching living rotifers coincided with a broader redefinition of zoology since the mid-nineteenth century, as Lynn Nyhart has shown for the German lands. Zoologists, in an attempt to challenge the increasing authority of physiologists, tried to sever the ties between their emerging discipline and its predecessor, natural history.[114] At the same time, zoologists appropriated research objectives and practices that had been closely associated with natural history, for instance life history studies.[115]

The Rotifera seemingly appealed to multiple readerships, ranging from French *micrographes* to German university professors. This does not mean that German zoologists considered Gosse and Hudson their equals. They were, after all, a science writer and a schoolteacher from rather provincial towns in Britain, whose book, to a large extent, continued the tradition of natural history writing. Rather, zoologists appropriated some elements of *The Rotifera*, such as the illustrations and life histories, to serve their own goal of discipline-building as argued by Nyhart. For instance, paired with Apstein's quantitative tables in *Das Süsswasserplankton*, Gosse and Hudson's illustrations were used to support what Apstein considered a "new era" of quantitative place-based biological research.[116] This reuse of Gosse and Hudson's morphological rotifer illustrations supports the argument made by Van Reybrouck, De Bont and Rock that researchers distributing artefacts to convince others of their research results lose in control what they gain in reach.[117] Originally intended to set Gosse and Hudson apart from metropolitan collectors, their rotifer illustrations came to be used by German zoologists to distinguish themselves from an earlier generation of natural historians.

The Rotifera was widely cited, but its lithographs were difficult and costly to reproduce. Just like the Royal Society illustrations which were included in Slack's manual and Ward's handbook, Gosse's simpler line drawings of rotifers published in his *Evenings at the Microscope* seem to have travelled further abroad than his lithographs. The illustrations in his book, "drawn on the wood direct from the microscope," were rather coarse, which perhaps made them less useful for classificatory purposes yet cheap and easy to reproduce.[118] It is no surprise, then,

[113] On Zacharias and Apstein's work, and the history of biological field stations in general, see Raf De Bont, *Stations in the Field: A History of Place-Based Animal Research, 1870-1930* (Chicago: University of Chicago Press, 2015).
[114] Nyhart, *Biology Takes Form*.
[115] Lynn K. Nyhart, "Natural History and the 'New' Biology," in *Cultures of Natural History*, ed. Nicholas Jardine, James Secord, and Emma C. Spary (Cambridge: Cambridge University Press, 1996), 426-441.
[116] Carl Apstein, *Das Süsswasserplankton: Methode und Resultate der quantitativen Untersuchung* (Kiel and Leipzig: Lipsius & Tischer, 1896), 3.
[117] See David Van Reybrouck, Raf De Bont, and Jan Rock, "Material Rhetoric: Spreading Stones and Showing Bones in the Study of Prehistory," *Science in Context* 22, no. 2 (2009): 195-216.
[118] Philip Henry Gosse, *Evenings at the Microscope*, 4-6.

that illustrations of rotifers included in *Evenings at the Microscope*, aimed at beginners in microscopy, came to feature in an American children's book on microscopy, *In Brook and Bayou* (1897) by Clara Kern Bayliss.[119] The reproduction of Gosse's illustrations in Kern Bayliss' book demonstrates that even in her fictional writing, rotifer illustrations were not only meant to be pleasant to look at. Rather, Kern Bayliss believed that in order to help children develop a keen scientific mind, one had to train their imagination, and her illustrated stories did just that.

Kern Bayliss, born in 1848, was the first woman to graduate from Michigan's Hillsdale College. She married the educator Alfred Bayliss, who in 1898 was elected Illinois Superintendent of Public Instruction. Kern Bayliss moved in similar circles, becoming head of the Education Committee of the Illinois Congress of Mothers and vice president of the Illinois State Teachers Association. She was also co-editor of the progressive *The Child-Study Monthly*, which encouraged a child-centred pedagogy and provided a publication outlet for the child study movement of the 1890s.[120] Kern Bayliss oversaw a section called the *Educational Current*, where she regularly commented on developments in education and reviewed books and articles. Many proponents of child studies, like G. Stanley Hall, the American leader of the child study movement, advocated for quantitative scientific methods to better understand the workings of the child's mind and improve the educational system. Clara Kern Bayliss's comments in the *Educational Current* suggest that she took a more pragmatic approach. She believed that parents needed to be educated along with their children and repeatedly argued that country clubhouses should be turned into centres for lifelong learning.[121] She wrote several children's books, which often blurred the line between fact and fiction and gave ample room to her readers' imagination. As she explained in the *Educational Current* of May 1899, a child's made-up stories should be regarded as "fiction in its earliest and crudest form, poems and novels by untrained hands" and be encouraged, not prohibited.[122]

In a column she wrote for *The Buffalo Enquirer* in 1899, Kern Bayliss encouraged the "young naturalist" to take along a microscope on his or her walks through the countryside whenever possible, as well as "cards of thick white paper" to draw anything of interest – "the colored pencilling will help to locate the food particles, the eyes, heart, eggs, etc."[123] In her book *In Brook and Bayou*, however, Kern Bayliss did not ask her young readers to sketch what they observed through

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[119] It is not clear if Gosse's illustrations were copied by hand or if his woodblocks were purchased to be used in Bayliss's book.
[120] Emily S. Davidson and Ludy T. Benjamin, Jr., "A History of the Child Study Movement in America," in *Historical Foundations of Educational Psychology*, ed. John A. Glover and Royce R. Ronning (New York: Springer Science+Business Media, 1987), 41-60.
[121] See Clara Kern Bayliss, "The Educational Current," *The Child-Study Monthly* 4 (1899): 425-432.
[122] Clara Kern Bayliss, "The Educational Current," *The Child-Study Monthly* 5 (1899): 49.
[123] Clara Kern Bayliss, "Vacation Studies for Young Naturalists – IX. Hidden Beauties of Ocean and Lake," *The Buffalo Enquirer*, 18 September 1899, 5.

the microscope. Gosse, in his *Evenings at the Microscope* had urged his readers to "[verify] . . . the observations here detailed."[124] Kern Bayliss, on the contrary, argued that the illustrations in *In Brook and Bayou*, many of which had been copied from Gosse's book, "[rendered] a microscope unnecessary."[125] Instead of teaching children how and what to see through the microscope, Kern Bayliss took her young readers on a journey into a microcosm inhabited by minute animals, mermaids, and a boy shrunk to microscopic size. Inserted into Kern Bayliss's book, Gosse's illustrations invited the reader to explore a spectacular microscopic world, half real and half imagined. In the preface, the author explained that she had written her book not only "for the purpose of enriching the child's life" but mainly "to please herself, and because she [was] fond of these microscopic creatures."[126] *In Brook and Bayou* was not much concerned with validating observations, and Gosse was no longer credited for his illustrations.

Kern Bayliss's book was one of Appleton's Home Reading Books, a series meant to "extend education beyond the school."[127] Yet the title of the book appears in many school library catalogues compiled around 1900. At the time, as Sally Gregory Kohlstedt has argued, educators advocating for nature study oriented American school education towards the hands-on examination of local plants and animals. Nature study sought to combine scientific textbooks with fictional nature writing, often portraying animals "with their own desires, fears, and thoughts, a technique that minimized the distinction between animals and humans."[128] Kern Bayliss' half-imagined microscopic world, including the adventures of a microscopic boy, seems to have appealed to teachers with an interest in nature study. *The Elementary School Teacher* recommended to use Kern Bayliss's book alongside magnifying glasses and pocket microscopes on school excursions.[129] It is probable, therefore, that the illustrations in *In Brook and Bayou* were sometimes used as intended by Gosse – as a means of authenticating both the illustrator's and the reader's observations. Just like the unforeseen travels of Gosse's illustrations, the use of *In Brook and Bayou* as a school textbook and guide to excursions had not been anticipated by its author. Despite being embedded in Kern Bayliss' fictional account, the illustrations that had resulted from Gosse's careful observations of rotifers still invited viewers to use them as visual field guides.

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[124] Philip Henry Gosse, *Evenings at the Microscope*, 4.
[125] Clara Kern Bayliss, *In Brook and Bayou. Or, Life in the Still Waters* (New York: D. Appleton and Company, 1897), 12.
[126] Kern Bayliss, *In Brook and Bayou*, 12.
[127] Kern Bayliss, *In Brook and Bayou*, v-vi.
[128] Sally Gregory Kohlstedt, *Teaching Children Science. Hands-on Nature Study in North America, 1890-1930* (Chicago: University of Chicago Press, 2010), 132.
[129] See Elsie A. Wygant, "Grade Outlines. Seventh Grade," *The Elementary School Teacher* 3 (1902-1903): 456-462.

Conclusion

This chapter set out to explore how circulating illustrations helped microscopists to teach themselves and others how to observe microscope specimens, taking reproductions of rotifer illustrations as a point of departure. The chapter was premised on the assumption that scientific observation is a multimedia affair, with microscopists triangulating among text, illustration and specimen. Illustrations were indeed crucial in making observations with the microscope. Not only did they show microscopists *what* to look for in a rotifer but also *how* to observe the animal. In Slack's book, most rotifer illustrations afforded observations made at one focus, so even users of cheap microscopes could compare what they saw through the microscope with the observations recorded by his wife, Charlotte Mary Slack. Slack also trained his readers' observational skills by linking unfamiliar microscopic forms to well-known objects through visual analogy. Gosse and Hudson invited the viewers of their illustrations to venture outside and collect living microscope specimens, while Mary Ward's illustrations suggested to her readers – among them probably many women and children – that household items could well be used to keep and observe rotifers.

The chapter has shown that image reuse was integral to scientific observation, especially at a time when new printing techniques and media, as well as increased competition in the literary market, afforded the reproduction of illustrations. Wood engravings were commonly reprinted, especially in books aiming at beginners in microscopy, as well as children. The autographic printing invented by Pumphrey further facilitated the reproduction of illustrations, making it possible for little-known authors to share their observations without having to go through a formal publication process. While the sprawling postal system enabled natural history dealers like Bolton to mail living microscopic plants and animals, Pumphrey's printing technique allowed for illustrations to be sent along with the specimens, giving natural history dealers an opportunity to suggest how their clients should interpret the microscopic plants and animals they received.

Reproducing illustrations allowed scientific authors and illustrators to appropriate them to some extent, and gradually renegotiate what should be considered good observational practice, or who counted as a reliable observer. Gosse, in his *Evenings at the Microscope*, urged beginners in microscopy to compare their observations with his wood engravings. In Mary Ward's *Microscope Teachings*, however, one of Gosse's rotifer illustrations appeared in the context of Ward's own observations made by repurposing cushions and wineglasses. Thus, each reproduction offered an opportunity for authors to promote different ways of observing microscopic creatures, and write, or draw, different groups of practitioners into the microscopy community, while building on the authority of previous observers. These attempts, however, were not equally successful. Since Thomas Bolton lacked proper scientific publications, his discovery of a new rotifer species was contested. Philip Henry Gosse, too, sometimes struggled to get the recognition he felt he deserved from scientific circles.[130] Yet, Gosse and Hudson's illustrations seemingly appealed to German zoologists, who tried to integrate some of the questions previously addressed by natural historians into their discipline. Since zoologists were interested in life histories and the morphological changes rotifers underwent, Hudson and Gosse's illustrations, "drawn from life," found an audience among them – and, being inserted into limnological studies, indirectly supported the place-based research emerging at biological field stations.

Although the chapter has shown that illustrations entered into conversation with new texts and images as they were reprinted, the observational practices of their producers and previous users remained inscribed in these illustrations. Clara Kern Bayliss, for example, invited her readers to regard her reprinted rotifer illustrations as a means of stimulating a child's imagination, but since the illustrations had resulted from Gosse's careful observation of rotifers, Kern Bayliss' book could still be used as a field guide – and teachers indeed used it on excursions. Whereas authors could make suggestions on how to use rotifer illustrations, they had little control over how readers and other authors actually (re)used them. Moreover, the reproduction of rotifer illustrations depended not only on the decisions made by the author, printer or publisher. The material qualities of the illustrations themselves and the things (or animals) involved in their production shaped their subsequent travels, too. Gosse's wood engravings, which could be reproduced cheaply, came to be included in Kern Bayliss' children's book. Likewise, the short lifespan of a microorganism sent through the post required Bolton's flyleaves to be printed and distributed swiftly, which impacted the quality of their illustrations.

In any case, illustrations of pond life were "working images," helping microscopists to probe with their hands what they saw with their eyes. Bolton's illustrator Forrest noted that drawing a specimen helped him to observe it more carefully, and that making a sketch of the specimen preceded its classification. The chapter has also shown that it is difficult to distinguish between private, messy sketches – "working images" in Nasim's original sense of the term – and their published, arguably more stable versions. Even after their publication, rotifer illustrations continued to be entangled with the observational practices of those who reused them, and they became objects of observation themselves. British biology students used reproductions of Gosse and Hudson's rotifer illustrations in order to learn to identify microscopic animals in the samples sent by Thomas Bolton. In the hands of Bolton's son, however, Gosse and Hudson's illustrations were as carefully studied as the rotifers themselves, teaching the illustrator how to draw scientific sketches by copying them.

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130 For example, Gosse's son Edmund recalled a dispute between his father and the Linnaean Society, which criticized the religious undertone of one of his papers. See Gosse, *Life of Philip Henry Gosse*.

Finally, the chapter has highlighted the importance of craftspeople in shaping scientific observation in the second half of the nineteenth century. Graeme Gooday has argued that science professionalisers like Thomas Huxley used the microscope to extend their own lab practices into the lecture hall and increase their scientific authority.[131] The chapter did not cast doubt on the influence of academics like Huxley or Lankester in interpreting microscopy, and science by way of it. But it has shown that these scientific luminaries relied on microscopists' infrastructures to supply themselves and their students with books, illustrations, all sorts of microscopy tools, and even living microscope specimens. Natural history dealers like Bolton and illustrators like the West brothers, although considered at the margins of the scientific community by many of their contemporaries, were crucial in making observations of microscopic life travel and relied on sprawling railway and postal networks to do so. While this chapter has only touched upon the central role of the post in supplying microscopists with illustrations and Bolton's living specimens, the following chapter expands on the importance of the British and American postal systems, arguing that they were vital in teaching geographically scattered microscopists how to make permanent microscope slides.

[131] See Gooday, "'Nature' in the Laboratory."

3 Sending Slides Through the Post: The British Postal Microscopical Society and the American Postal Microscopical Club

When Romyn Hitchcock, editor of the *American Monthly Microscopical Journal*, opened a box of microscope slides he had received through the post in 1883, he was “pleased to find the slide of Spirogyra which [he] contributed long ago.”[1] Hitchcock was a member of the American Postal Microscopical Club, which facilitated the exchange of slides among its members. Club members circulated slide boxes, as well as explanatory notes and illustrations, following a chain-letter principle. Every member received microscope preparations and notes and was expected to pass them on to other members in his or her postal circuit in due time. Hitchcock’s *Spirogyra*, a freshwater green alga, had been passed on among microscopists for around two years before it finally circled back to him, “after a varied experience in mail-bags and in different climes.”[2]

When the club was formed in 1875, there were already some twenty microscopy societies in existence in the United States, most of which had been established along the Northeast coast and in the Great Lakes region in the early 1870s.[3] Although several societies lasted only a couple of years, by 1893 their overall number had risen to fifty-four.[4] Society members were usually based in the same city or its close surroundings and met regularly. The American Postal Microscopical Club, however, drew members from all over the country. It consisted of only around 140 members during most of its history, but it was not the only postal club of its kind. It was explicitly modelled on the British Postal Microscopical Society, founded in 1873, which facilitated the exchange of microscope slides on the other side of the Atlantic.[5] In the German lands, at least two large postal exchanges of slides had been organised by the microscopy society of Giessen in the 1850s.[6] In 1884, the *Journal of Microscopy and Natural Science*, associated with the British Postal Microscopical Society, reported that a postal microscopy club had been founded in

[1] Romyn Hitchcock, "Editorial," *American Monthly Microscopical Journal* 4, no. 4 (1883): 76.
[2] Ibid.
[3] See John Harley Warner, "‘Exploring the Inner Labyrinths of Creation’: Popular Microscopy in Nineteenth-Century America," *Journal of the History of Medicine and Allied Sciences* 37, no. 1 (1982): 7-33.
[4] See John Phin, "Microscopical Societies in the United States and Canada," *The American Journal of Microscopy and Popular Science* 1, no. 6 (1876): 72-73; Charles W. Smiley, "List of Microscopical Societies," *The Microscope* 1, new series, no. 8 (1893): 119-122.
[5] Frederic Ward Putnam and Alpheus Spring Packard, "Microscopy," *The American Naturalist* 9, no. 4 (1875): 249.
[6] See "Tauschverkehr Mit Mikroskopischen Präparaten," *Archiv für pathologische Anatomie und Physiologie und für klinische Medicin* 14, no. 5/6 (1858): 556-557.

Australia.[7] While there were postal microscopy societies outside the United States and Britain, the American and British organisations were the first of their kind, and lived the longest – the British Postal Microscopical Society exists to this day. Late-nineteenth-century postal clubs were not confined to microscopy either – several postal photography societies were established in the United States and Britain in the 1880s and 1890s.[8]

The declared mission of the American Postal Microscopical Club and the British Postal Microscopical Society was to educate microscopists on how to make microscope preparations. Scientifically noteworthy specimens were much valued, but members of the club and society were equally interested in making permanent slides. Hitchcock's *Spirogyra* was not a very remarkable plant, being commonly used in schools to illustrate the process of conjugation between algae, but club members who received his slide were curious to know how Hitchcock had stained his alga with carmine.[9] The editor readily explained the method in his journal, giving detailed instructions and pointing out possible pitfalls.[10] When Hitchcock received his slide back in 1883, "just as perfect as when it left [his] hands," he saw it as proven that his slide was durable.[11]

Just like making observations with the help of the microscope, preparing and mounting microscope specimens required technical skill, a kind of craft knowledge that was often difficult to learn through written instructions. Illustrating the benefit of practical experience for mounting specimens, Hitchcock's journal cited the English slide maker Edward Ward in 1883: "[We] have, early in our work, learned that there is a difference, and a vast one, between knowing that an object is mounted in Canada Balsam and being ourselves able to mount in this medium."[12] Ward emphasised the importance of on-site collaboration, recalling how several English gentlemen had met to practice mounting together, with their "fingers being Canada Balsamed up to the knuckles."[13] However, members of

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[7] See Henry Watts, "Correspondence," *Journal of Microscopy and Natural Science* 3, new series (1884): 261-262.

[8] On the American Postal Photographic Club, see C. W. Canfield, "A Postal Photographic Club," *Anthony's Photographic Bulletin* 16, no. 4 (1885): 105. An English postal photography club for boys is mentioned in Jochen Petzold, "Victorian Gendered Photography in the Boy's Own Paper and the Girl's Own Paper," *Victorian Periodicals Review* 52, no. 1 (2019): 57-79. Another postal club for exchanging animal photographs was founded in Selborne, England; see "Selborniana," *Nature Notes: The Selborne Society's Magazine* 10, no. 114 (1899): 104. For an in-depth discussion of postal photography clubs, see Sara Dominici, "The Postal Service, Circulating Portfolios and the Cultural Production of Modern Networked Identities," *History of Photography* 44, no. 2/3 (2020): 111-127.

[9] For an example of Spirogyra being used in education, see Asa Gray, *Gray's School and Field Book of Botany* (New York: American Book Company, 1887).

[10] See Romyn Hitchcock, "Notes," *American Monthly Microscopical Journal* 2, no. 8 (1881): 158-159.

[11] Hitchcock, "Editorial," 76.

[12] Romyn Hitchcock, "Mounts and Mounting," *American Monthly Microscopical Journal* 4, no. 8 (1883): 149.

[13] Hitchcock, "Mounts and Mounting," 150. Stephen Jacyna has shown that Edinburgh histologists sought to cultivate an intimate relationship between instructors and students to teach microscopy. Jacyna, "'A Host of Experienced Microscopists'."

postal clubs and societies did not usually meet in person. How, then, did these organisations still make it possible for members to learn preparation methods?

Since members of postal clubs and societies were not able to acquire knowledge through "the imitation of bodily gestures" in a workshop setting, members crafted their own infrastructures, a virtual workshop of sorts, to allow for preparation methods to be shared among them.[14] These infrastructures consisted of distributed notebooks, low-brow science journals, trade papers and catalogues, and, importantly, the postal system, with members of the American Postal Microscopical Club effecting a change of the American postal law to facilitate the exchange of slides. As this chapter shows, late-nineteenth-century postal infrastructures set up by microscopists were fragile and required much maintenance. The vulnerability of postal clubs and societies was frequently addressed and well documented by their members, and both the American Postal Microscopical Club and the British Postal Microscopical Society appointed secretaries and other officers, who were in charge of organising the postal exchange.

Building on Karasti and Blomberg's work, the methodological section of the introduction has argued that although everyday users of infrastructures may not be aware of them as long as they function smoothly, infrastructures remain a matter of concern to their maintainers, "members [who] themselves engage in activities of infrastructural inversion."[15] Karasti and Blomberg point to Elena Parmiggiani's research into the infrastructures of subsea environmental monitoring, and her methodological decision to identify and follow a "subset of actors who, as part of their daily work, were in charge of answering the same questions [she] had to answer as part of [her] research."[16] Thus, by following the maintainers of infrastructures, we can achieve infrastructural inversion, rendering infrastructures more noticeable and researchable. While the previous chapter tracked reproductions of illustrations which carried traces of their exchange among different groups of microscopists, this chapter follows the historical actors who organised and maintained postal exchanges of microscope slides.

In doing so, the chapter also lays bare the craft knowledge shared with the help of these infrastructures. There has recently been an increase in research at the intersection of the history of science and communications, for example Laura Newman's work on postal pathology in the early twentieth century, or Matt Wale's investigation of the role of the post in exchanging entomological specimens in the nineteenth century.[17] Jeremy Vetter has observed that mailing natural history

[14] Smith, "In a Sixteenth-Century Goldsmith's Workshop," 41.

[15] Karasti and Blomberg, "Studying Infrastructuring Ethnographically," 251.

[16] Elena Parmiggiani, "Integration by Infrastructuring: The Case of Subsea Environmental Monitoring in Oil and Gas Offshore Operations" (PhD dissertation, Norwegian University of Science and Technology, 2015).

[17] See Laura Newman, "'Death Germs through the Post': Postal Pathology and Workplace Experiences of Disease in Britain, C.1895–1935," *Social History of Medicine* 33, no. 4 (2020): 1211-1232; Wale, "'The Sympathy of a Crowd'." See also Vennen, *Das Aquarium*.

specimens in the American railroad era "constituted both an act of material transport and an act of scientific communication."[18] This chapter builds on Vetter's observation, showing how a microscopist's skill in making slide preparations came to be inextricably intertwined with his or her skill in navigating knowledge infrastructures. In trying to circulate slides, microscopists had to make sure that both their skills and infrastructures were up to the task. For example, the fragility of the chain-letter system required microscopists to develop weather-resistant mounts of specimens and refrain from making and circulating preparations that might break or spill during their travels. The postal exchange thus shaped microscopists' mounting practices and their preference for certain materials and techniques. Consequently, infrastructural inversion, tracing the infrastructures built and used by craftspeople, allows us to examine not only infrastructures themselves but also the craft knowledge they helped to share.

The chapter first situates the American Postal Microscopical Club and the British Postal Microscopical Society in the wider landscape of microscopy organisations and their publications in the late nineteenth century, showing how microscopists' postal circuits emerged from pre-existing physical and virtual sites of knowledge production. Then, the chapter turns to the two postal organisations, examining the development of their postal circuits, before zooming in on the slides exchanged and how members learned to make them. The final section investigates how the members' craft came under public scrutiny in the pages of microscopy periodicals. The chapter concludes by summarising the strategies microscopists developed to meet the challenge of producing microscope slides together despite being scattered across the United States and Great Britain.

Microscopy Clubs and Societies in Great Britain and the United States

Although microscopy was also on the rise in France and the German lands around the mid-nineteenth century, it was only in Great Britain and, later, the United States, that the research field of "microscopical science" was formalised through a wealth of journals and societies dedicated to microscopy.[19] The Royal Microscopical Society (RMS), then the Microscopical Society of London, was the first society of its kind when it was founded in 1839. Many of its founders and early members were medical practitioners who advocated for the use of the microscope in medicine and medical education.[20] In the 1830s, microscopy became popular with phy-

[18] Jeremy Vetter, *Field Life: Science in the American West During the Railroad Era* (Pittsburgh, PA: University of Pittsburgh Press, 2016), 94.
[19] See Brock, "Patronage and Publishing."
[20] See Gerard L'E. Turner, "The Origins of the Royal Microscopical Society," *Journal of Microscopy* 155, no. 3 (1989): 235-248.

sicians on the European continent and in Britain, as they began to turn to pathological anatomy and achromatic compound microscopes came into wide use.[21] The RMS, established only a year after Theodor Schwann proposed his cell theory, gave the new histological approach a physical home in London. To join the RMS, microscopists had to pay an entrance fee of £1 and an additional annual fee of £1, which was raised to £2 after the society was granted a Royal Charter in 1866.[22] Whereas an engineer at the time may have made £100 a year, an agricultural labourer was more likely to live on around £30 per annum, so the membership fees of the RMS amounted to more than a month's worth of salary for many workers.[23] As a result, the RMS Fellows mainly consisted of middle- and upper-class medical practitioners, eminent academics and instrument makers, and membership rose only gradually.[24]

In the 1860s and 1870s, the RMS was joined by a new generation of local natural history societies and field clubs, which, as Sam Alberti and others have shown, targeted the middle-classes, who had begun to pursue science in their after-work hours.[25] Middle-class microscopy societies, too, became more numerous in Great Britain. The London Quekett Microscopical Club, founded in 1865 as a more affordable and accessible alternative to the rather elitist RMS, gave impetus to the rise in microscopy societies. Like the RMS, microscopy clubs and societies of the 1860s and 1870s provided ample opportunity for microscopists to observe microscope specimens together. Regular meetings, as well as occasional public soirees and exhibitions, allowed members to present papers, observe microscope slides, judge preparation techniques, and assess the instruments used to make observations. Moreover, many societies, and especially the field clubs founded from the 1860s onwards, organised field excursions, where society members would learn where and how to find specimens, how to collect them, and how to recognise specimens of scientific interest.[26]

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[21] See La Berge, "Debate as Scientific Practice;" La Berge, "History of Microscopy."

[22] See The Microscopical Society of London, "Constitution and Laws of the Microscopical Society of London," *The Transactions of the Microscopical Society of London* 14, new series (1866): 107-115; James Glaisher, "The President's Address for the Year 1866," *Transactions of the Microscopical Society of London* 14, new series (1866): 45-63.

[23] See Dale H. Porter, *The Thames Embankment: Environment, Technology, and Society in Victorian London* (Akron, OH: University of Akron Press, 1998); Michael Turner, "Agriculture, 1860–1914," in *Economic Maturity, 1860–1939.* Vol. 2 of *The Cambridge Economic History of Modern Britain*, ed. Paul Johnson and Roderick Floud (Cambridge: Cambridge University Press, 2004), 133-160.

[24] See Turner, "The Origins of the Royal Microscopical Society."

[25] See Samuel J. M. M. Alberti, "Amateurs and Professionals in One County: Biology and Natural History in Late Victorian Yorkshire," *Journal of the History of Biology* 34, no. 1 (2001): 115-147.

[26] See Anne Secord, "Pressed into Service: Specimens, Space, and Seeing in Botanical Practice," in *Geographies of Nineteenth Century Science* ed. David N. Livingstone and Charles W. J. Withers (Chicago: University of Chicago Press, 2011), 283-310. Unlike other collectors, microscopists faced the additional difficulty of having to rely on magnifying glasses or portable low-power microscopes to decide which samples of water or bits of plants were worth taking home for closer examination.

Societies also spurred the standardisation of instruments. The RMS, for example, introduced standards for microscope slides (the 3 x 1 inch slide) and a universal screw thread which allowed microscopists to combine microscope stands and objectives from different manufacturers.[27] Both the standard slide and screw thread reveal the complex relationship between standardisation and flexibility in sharing observations. While these standards limited the variation in slides and threads, both were a prerequisite for ensuring the interoperability of microscopists' tools.[28] Crucially, as the following section shows, the chain-letter system of the American Postal Microscopical Club and the British Postal Microscopical Society relied on standard-sized slides and slide boxes, since slides that did not fit properly into the slide boxes circulated by microscopists risked breakage.

It is difficult to estimate how many microscopy societies were established in Great Britain from the 1860s onwards, since many did not publish their proceedings, met irregularly in someone's home, or were merely divisions within a natural history society. Yet, the map below shows a rough estimate of the number and geographical distribution of these organisations (Fig. 3.1). The map draws on lists of microscopy clubs and societies published by natural history periodicals at the time. These lists often included societies with a strong link to microscopy but whose name did not signify that their main interest lay in microscopy. In addition to societies mentioned in contemporary lists, the map includes societies whose proceedings were regularly printed or summarised in the long-running *Quarterly Journal of Microscopical Science*, in RMS publications and, to counter the potential geographical bias of these London-based publications, microscopy societies mentioned in *The Microscopical News and Northern Microscopist*.[29] The map indicates that microscopy societies culminated in and around London, as well as in Northern England. Microscopy societies thus largely mapped onto the British industrial centres at the time. The distribution of societies also matches Alison Morrison-Low's finding that microscope manufacturers in the North contested London's reputation as the centre of scientific instrument making.[30] Like London's in-

[27] Of course, the standardisation of both slides and threads hinged on the cooperation of microscope manufacturers, most of whom were themselves society members. See A. W. Anderson, "How the Bausch & Lomb Optical Company Works out Its Standardization Program," *Industrial Standardization and Commercial Standards Monthly* 9, no. 9 (1938): 201-208; Savile Bradbury, *The Evolution of the Microscope* (London: Pergamon Press, 1967).
[28] As Ole Hanseth, Eric Monteiro and Morten Hatling note, sometimes "standardization is a precondition for flexibility." Ole Hanseth, Eric Monteiro, and Morten Hatling, "Developing Information Infrastructure: The Tension between Standardization and Flexibility," *Science, Technology, & Human Values* 21, no. 4 (1996): 416.
[29] The few Scottish and one Irish society documented in English publications do not seem to have reported on the activities of other Scottish or Irish societies in their proceedings, making it difficult to estimate the number of societies in Scotland and Ireland.
[30] See Morrison-Low, *Making Scientific Instruments in the Industrial Revolution*.

strument makers, Northern manufacturers were embedded in a dense web of microscopy societies and, judging from the society proceedings published in Northern periodicals, many manufacturers were themselves society members.

Figure 3.1 Map of British microscopy societies and natural history societies with a strong link to microscopy, established between 1860 and 1900. Only a few of these societies survived until (or after) the end of the century. Map data: Google, INEGI.

Microscopy societies were also the primary publishers of microscopy periodicals, ranging from society proceedings to more comprehensive scientific journals. According to William Brock's thorough review of microscopy periodicals established in nineteenth-century Europe and America, of the nineteen British periodicals, thirteen were at least temporarily associated with societies.[31] Periodicals were crucial in establishing networks that reached far beyond the members who attended

[31] See Brock, "Patronage and Publishing."

society meetings. In the case of the RMS, by the late nineteenth century, many of its Fellows lived abroad, scattered across Europe, North America and the British colonies. These international Fellows, as well as British Fellows who lived too far removed from London to attend meetings, relied on the RMS journal to stay abreast of developments in British microscopy.

Most societies circulated their periodicals not only among their members but also made them available to external subscribers. As Brock has shown, some societies relied to a large extent on subscription fees to finance their publications. Whereas members often received periodicals free of charge, external subscribers subsidised members' subscriptions by paying substantial sums for their own issues.[32] The RMS, like many societies, also exchanged their publications with other microscopy and natural history societies, which did not help to bolster the society's finances but made the latest publications available to RMS Fellows. James Glaisher, then president of the RMS, claimed in 1869 that it was the society's journal that enabled members to "establish useful . . . relations with other excellent Microscopical Societies, both in the metropolis and scattered throughout the country."[33]

Importantly, the activities of microscopy societies, and natural history societies more broadly, extended into the pages of their publications. Geoff Belknap, James Mussell, and other historians of the periodical press have shown that periodicals shaped a range of collaborative scientific practices.[34] The correspondence columns in periodicals made it possible for readers to exchange both observations and specimens, while the seriality of the periodical shaped the succession of society events throughout the year, and vice versa.[35] In his study of *Notes & Queries*, a British periodical much beloved by antiquarians, Patrick Leary argues that the periodical constituted a veritable "virtual community" of reader-contributors.[36] As its title suggests, *Notes & Queries* invited its readers to share and discuss antiquarian findings, and its correspondence column became a public forum for lively discussions. A "virtual community" emerged in the pages of *Notes & Queries*, with its own rules of conduct and markers of identity. This capacity of the periodical press to build virtual scientific communities was a crucial factor in the emergence of postal societies. Especially in the case of the American Postal Microscopical Club, as I will show, the organisation of the chain-letter correspondence relied to a large extent on reports published in periodicals.

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32 Ibid.
33 James Glaisher, "The President's Address," *The Monthly Microscopical Journal* 11 (1869): 146.
34 See Belknap, "Illustrating Natural History;" Wale, "'The Sympathy of a Crowd'."
35 See Mussell, *Science, Time and Space in the Late Nineteenth-Century Periodical Press: Movable Types*.
36 See Leary, "A Victorian Virtual Community." See also Belknap, "Illustrating Natural History."

Figure 3.2 Map of microscopy societies in the United States that existed between 1876 and 1893, according to two lists of societies published in these years. In 1893, Charles W. Smiley, editor of *The Microscope*, reported that 15 of formerly 70 societies had died within the past three or four years. Map data: Google, INEGI.

Microscopy societies and periodicals also flourished in the United States, where the first microscopy society appears to have been established in New York City around 1840. Like the RMS Fellows, its first members had a background in medicine. However, evidence concerning this society, as well as two or three more societies established before the 1870s, is scarce, and these societies seem to have existed only a few years.[37] It was only in the 1870s, after the Civil War, that microscopy clubs and societies began to multiply. As in the case of British societies established from the 1860s onwards, the overall number of American microscopy organisations in the second half of the nineteenth century is difficult to estimate, since many of them were divisions of broader natural history societies, no more than small private gatherings, or ephemeral organisations that disappeared after a short time. However, editors John Phin and Charles W. Smiley reviewed the development of microscopy societies in 1876 and 1893, recording both existing and extinct societies, which makes it possible to map their distribution at least roughly (Fig. 3.2).[38] The map shows that most microscopy clubs and societies were founded along the East Coast and in the industrial centres in the Great Lakes region, but several organisations were established further south and west.

[37] Evidence of these societies is based on the recollections of William Henry Seaman, professor of chemistry at Howard University, Washington, DC. See William Henry Seaman, "Microscopical Societies and Microscopy," *The American Monthly Microscopical Journal* 6 (1885): 87-89.
[38] Smiley also solicited reports of Canadian societies, but only three were included in his list of 1893: the Microscopical Section of the Entomological Society of Ontario, the Montreal Microscopical Society, and the Victoria Natural History Society. Charles W. Smiley, "American Societies Interested in Microscopy," *The Microscope* 1, new series (1893): 9-11.

The historian of science and medicine John Warner describes American microscopy societies as similar to their British counterparts: American societies, too, were middle-class organisations providing both formally trained and self-trained scientific practitioners with opportunities to present slides, instruments and scientific papers.[39] Elizabeth Keeney, in her work on nineteenth-century American botanists, writes that after the establishment of the Smithsonian Institution in 1846 and the American Association for the Advancement of Science in 1848, the distinction between professional scientists with academic training and self-trained "botanisers" became more pronounced, and more distinctly professional societies emerged towards the end of the century.[40] Warner, however, argues that microscopy societies continued to serve as crucial links between science and leisure, education and entertainment, well into the late nineteenth century. Many young scientists and physicians, attending society meetings and being instructed by more senior members from an early age, would begin to use microscopes in their professional work. At the same time, society meetings, as well as exhibitions and sociable soirees, gave physicians an opportunity to present themselves as scientific authorities on medical questions to their fellow members (and potential patients).[41]

The spread of American microscopy societies from the 1870s onwards was accompanied by a rising number of microscopy periodicals. Like British periodicals, the American microscopy periodical press was often published by societies. William Brock counts eleven American microscopy periodicals published in the nineteenth century, with at least five of them associated with microscopy or natural history organisations.[42] Two American periodicals were published by microscope manufacturers, Bausch & Lomb and James W. Queen & Co., respectively. While some British microscope manufacturers published comprehensive trade catalogues that included information on the use of their scientific instruments, the American companies Bausch & Lomb and James W. Queen & Co. carefully fashioned their publications as scientific periodicals first, trade catalogues second.

Despite the many similarities between British and American microscopy societies and periodicals, in terms of their organisation and middle-class members, British and American microscopists were, of course, embedded in different national contexts. One vast difference, which was essential in organising postal societies, was that American microscopists were more dispersed in space than their British contemporaries. As Jeremy Vetter has argued, railroads, the telegraph and the post helped to connect American scientific workers in the field in the second

[39] See Warner, "'Exploring the Inner Labyrinths of Creation'."
[40] See Elizabeth B. Keeney, *The Botanizers: Amateur Scientists in Nineteenth-Century America* (Chapel Hill and London: University of North Carolina Press, 1992).
[41] See Warner, "'Exploring the Inner Labyrinths of Creation'."
[42] See Brock, "Patronage and Publishing."

half of the nineteenth century, but these infrastructures grew unevenly.[43] Likewise, postal societies, as well as the migratory national American Microscopical Society, helped to bring together geographically dispersed scientific practitioners. However, the organisation of postal societies itself hinged on the functioning of established infrastructures, such as the periodical press and the postal system, which, in the case of American Postal Microscopical Club, turned out to be less reliable than the club's officers had hoped.

The following section examines the emergence of the British and American postal microscopy societies in the 1870s, which were inspired by the physical microscopy societies that had been founded earlier. The British and American postal systems were vital in enabling microscopists to work together and learn how to make permanent slides despite being scattered across Great Britain and the United States. Although the members of the British Postal Microscopical Society experienced occasional breakages and losses of slides in the post, their exchange functioned smoothly overall – their chain-letter system continues to this day. The network of the American Postal Microscopical Club was more fragile and required a change of the postal law to function. Therefore, after tracing the beginnings of both the British and American postal organisations, the next section focuses on how the American Postal Microscopical Society and the American post co-developed from the 1870s onwards.

Establishing Postal Circuits for Microscopists

Given the importance of periodicals in building (virtual) scientific communities, it may not be surprising that both the British Postal Microscopical Society and the American Postal Microscopical Club were born in the pages of periodicals.[44] The British society was established in 1873, after a reader of *Hardwicke's Science Gossip*, Alfred Atkinson, a civil engineer from Lincolnshire, sent a letter to the periodical asking if other readers would be interested in forming a "postal cabinet association."[45] Atkinson outlined the basic principles of this association, explaining that a box of slides would be sent from one microscopist to the next and each would be asked to add a slide to the box and send it on to the next member. Atkinson's idea was taken up by another correspondent of *Science Gossip*, Alfred Allen, a grocer and wine merchant based in Essex and, later, Bath. Together, Atkinson and Allen drew up the rules of their new association, which grew to 36 members in its first year, and counted 147 members by 1882. Atkinson became the first president of the fledgling society, while Allen was appointed secretary.

[43] See Vetter, *Field Life*.
[44] The Quekett Club, too, was born in the pages of *Science Gossip*. See Belknap, "Illustrating Natural History."
[45] Alfred Atkinson, "Microscopic Postal Cabinets," *Hardwicke's Science Gossip* 9 (1873): 111.

In his letter to *Science Gossip*, Atkinson acknowledged that his idea for a "postal cabinet association" was inspired by manuscript magazines, handwritten magazines compiled and circulated by a small group of reader-contributors.[46] As Catherine Sloan and other historians of juvenile print culture have shown, circulated manuscript magazines were ubiquitous in the late nineteenth century but have received relatively little attention from scholars of print culture.[47] Sloan emphasises the emancipatory function of manuscript magazines, which enabled their young authors to circulate their own writing without interference of editors and publishers, much like Thomas Bolton's flyleaves duplicated through autographic printing. Likewise, the notes circulated by the British Postal Microscopical Society made it possible for anyone interested in microscopy to share their observations with like-minded individuals without editorial approval, which was especially welcomed by microscopists who did not have access to local field clubs and societies. Women, who were barred even from London's low-brow Quekett Microscopical Club, could join the postal society, and, judging from the society's list of correspondents, at least eleven women had joined by 1882.[48]

Moreover, some of the most committed members of the British Postal Microscopical Society and the American Postal Microscopical Club had had their careers destroyed by bad health, were disabled, or altogether homebound. For instance, as mentioned in the previous chapter, the illustrator and member of the British Postal Microscopical Society Tuffen West was deaf, owing to an explosion in his father's lab. Mary Ann Booth, a member of, and regular commentator on, the American Postal Microscopical Club, was described as an "invalid in a chair" in an article in the *Illustrated World* entitled "The Irregulars of Science."[49] Alfred Allen, co-founder of the British Postal Microscopical Society, retired early, probably due to poor health, and moved to the spa town of Bath. The diversity of their members shows that postal microscopy associations made it possible for microscopists to overcome not only their geographical isolation but, to some extent, also the social immobility and isolation experienced by some of them due to their gender or disabilities. Thanks to the postal club and society, microscopists in both the geographical and social margins of the scientific community could continue to pursue their interests and find companionship in correspondence and periodicals.

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[46] See Atkinson, "Microscopic Postal Cabinets."

[47] See Catherine Sloan, "'Periodicals of an Objectionable Character': Peers and Periodicals at Croydon Friends' School, 1826–1875," *Victorian Periodicals Review* 50, no. 4 (2017): 769-786; Lois Burke, "'Meantime, It Is Quite Well to Write': Adolescent Writing and Victorian Literary Culture in Girls' Manuscript Magazines," *Victorian Periodicals Review* 52, no. 4 (2019): 719-748; Kathryn Gleadle, "Magazine Culture, Girlhood Communities, and Educational Reform in Late Victorian Britain," *The English Historical Review* 134, no. 570 (2019): 1169-1195.

[48] This only includes members listed as "Miss" or "Mrs." in the society's list of members. Some women may have joined the society using only their initials or their husband's name.

[49] See William H. Dearden, "The Irregulars of Science. How Men Working in Attic and Coal-Bin Laboratories Are Building up the World's Knowledge, " *Illustrated World* 14, no. 4 (1915): 450-455.

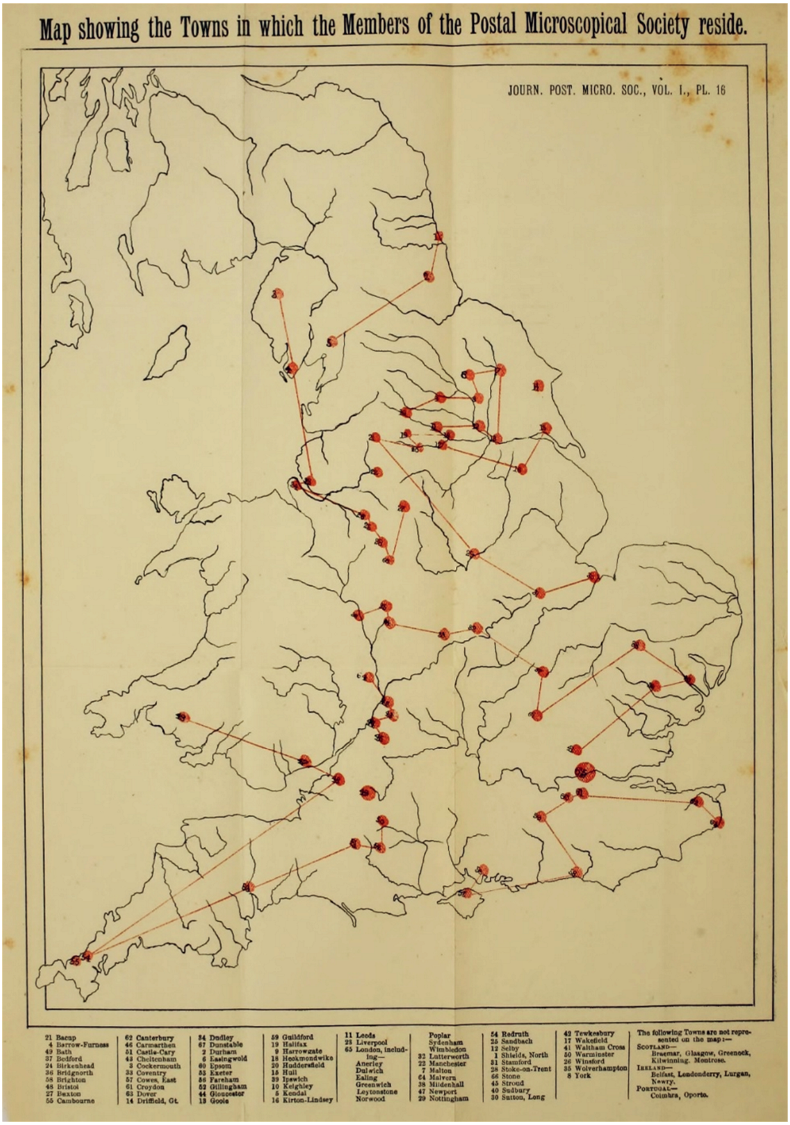

Figure 3.3 Map of circuits of the British Postal Microscopical Society, 1882. Image from the Biodiversity Heritage Library. Contributed by the MBLWHOI Library.

Members of the British Postal Microscopical Society were organised into circuits of twelve microscopists each and asked to fill a slide box with one microscope preparation, add explanatory notes or illustrations in a separate letter package, and then pass both on to the next member in their circuit. The members were urged to send the box and notes to the next person after no more than three evenings, which indicates that most of their members worked during the day and could only dedicate their after-work hours to microscopy. Once the box and notes had completed the circuit, they were sent back to the secretary, who sent them to the next circuit, and so on. The map below (Fig. 3.3) illustrates the geographical distribution of members in 1882. Comparing this map with the distribution of microscopy societies (Fig. 3.1), it is evident that the postal society managed to connect at least a few microscopists who lived remote from microscopy societies in Wales, Devon, Cornwall, and even Ireland, Scotland and Portugal.[50]

In his 1873 proposal for a "postal cabinet association," Atkinson had suggested to charge an entrance fee of one shilling and another shilling as annual subscription fee, but by 1882, these fees had risen to five shillings each.[51] This, and the fact that members had to use their own microscopes to examine the slides, firmly established the society as a middle-class organisation. Yet, as Richard H. Moore, then president of the British Postal Microscopical Society, noted in 1896, the reach of the society went beyond its middle-class members:

> In one of our earlier note-books a member relates his experience somewhat as follows: After an evening spent in examining one of our boxes, he left his microscope with the 1/4-inch objective attached, and sundry slides on his study-table, and was much annoyed in the morning to find one of the slides smashed and the 1/4-inch objective totally destroyed. On enquiry he learned that his maidservant had been doing her microscopy before breakfast![52]

Just like manuscript magazines, the notes and slides of the British Postal Microscopical Society were embedded in the domestic sphere, which, as Moore remarked, made microscopy accessible to members' "wives, children, friends … and maidservants" and put the society in "the unique position of affording scientific instruction and recreation in the home."[53] The British Postal Microscopical Society had set out to connect geographically dispersed microscopists, but there is no evidence that its founders deliberately designed it to accommodate diverse practitioners who were marginalised in other scientific societies. Yet Moore's positive response to a member's maidservant examining the circulated slides shows that the postal society soon embraced its role as providing informal education to microscopists who were for one reason or another bound to their homes. Thus, at a time when professional science moved outside the home and into the lab, postal societies continued to make the home a place of knowledge production, even if

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[50] Members in Ireland, Scotland and Portugal are not included in the map but in the list of society members beneath.
[51] See "Rules," *The Journal of the Postal Microscopical Society* 1 (1882): 5-8.
[52] Richard H. Moore, "Presidential Address," *International Journal of Microscopy and Natural Science* 6, 3rd series (1896): 2.
[53] Moore, "Presidential Address," 2.

microscopy in the domestic sphere was considered primarily educational by many.[54]

Unlike the American Postal Microscopical Club, the British society also provided opportunities for members to meet outside their homes. While the president, secretary and other officers of the society were certainly focused on establishing a postal community – and even invited members to submit their *cartes de visite* so they could be arranged as a group photo – some of the members met in London once a year, and others began to form local circles or societies of their own. Although the postal society sometimes lost microscopists to these newly established organisations, the society's officers encouraged members to form virtual and physical sub-groups based on geographical proximity or similar interests. In 1885, for example, a medical section was established to better accommodate the interests of the society's many medical members.[55] Moreover, the map (Fig. 3.3) shows that in some circuits members were based in the same city, so some members may have known each other even before joining the British Postal Microscopical Society.

Meeting at least occasionally made it easier for members to get to know and learn from one another, while a physical headquarters set up in Bath helped to organise the society's postal exchange. By 1882, Alfred Allen and a few other members located in Bath had formed a sub-committee whose task it was to handle "all acts of detention of boxes, damage to, or non-circulation of slides, or any other acts of irregularity."[56] Despite these efforts, the society grappled with delayed and broken slides, which threatened to destabilise the chain-letter network. This is indicated by several revisions of the rules of the society. Whereas Allen had initially proposed a "very brief" set of rules in 1873, some ten years later, the rules covered the handling, packaging and forwarding of slides, as well as liability rules in case of breakage and an optional insurance for slides. Overall, however, British microscopists managed to build and maintain their postal circuits without much trouble, at least in comparison with the American Postal Microscopical Club. Since members of the American club were more geographically dispersed than British microscopists, most of them never met in person, and their circulation of slides was even more reliant on (and constrained by) the postal system.

When the British Postal Microscopical Society was founded in 1873, American microscopists still considered British microscopy with its many societies, periodicals and broad public support a model to emulate, and the new postal organisation soon sparked interest on the other side of the Atlantic. Only two years later,

[54] For a study of the long history of domestic science, see Alix Cooper, "Homes and Households," in *Early Modern Science*, ed. Katharine Park and Lorraine Daston (Cambridge: Cambridge University Press, 2006), 224–237.
[55] See "Our Annual Meeting," *The Journal of Microscopy and Natural Science* 4 (1885): 46-54.
[56] "Rules," 5.

in 1875, the American Postal Microscopical Club was established, after *The American Naturalist* issued a call to recruit members for a postal microscopical club. The journal published the rules of the club and informed its readers that applications for membership could be sent to the journal or the club's provisional secretary.[57] Since the club was explicitly modelled on the British Postal Microscopical Club, the rules of the two organisations were similar. The American club's postal circuits, too, consisted of twelve members each. The club's secretary would send an empty slide box to one member in each circuit, who would add a slide, as well as notes and illustrations in a letter package, and forward both to the next person in his or her circuit. Members were asked to send the box and notes to the next person after no more than four days.[58] Once the box and notes had completed the first circuit, they were sent back to the secretary, who sent them on to the next. In the beginning, the annual membership fee was fifty cents, which was later raised to one dollar.[59]

Only one year after its foundation, the club consisted of twenty-four circuits, then counting six members each, who received one or two boxes of slides per month (Fig. 3.3). As stated in the club's report of 1876, it took "two years for a slide to make the entire round, and in doing this it must travel not less than thirty thousand miles by mail."[60] The number of circuits seems to have remained relatively stable over the following fifteen years.[61] The officers of the club were careful only to admit members if there were vacant spots available in existing circuits, or if the new members could form a circuit of their own.[62] Members were expected to contribute at least one slide per year, "preferably one illustrating some new method of preparation, or result of study."[63] The slides had to be numbered corresponding to the owner's position in the circuit, so they could easily be attributed to them. From the outset, as in the British Postal Microscopical Society, women could join, yet there were no female microscopists in the circuits established by 1876.[64]

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[57] See Putnam and Packard, "Microscopy."
[58] Ibid. This was later changed to three days, see "Queries," *American Monthly Microscopical Journal* 9, no. 8 (1888): 155.
[59] Fifty cents is the sum mentioned in *The American Naturalist* by Putnam and Packard, "Microscopy." The raise is documented in "Queries."
[60] Charles R. Dodge, "Editorial Pencillings," *Field and Forest* 2, no. 8 (1877): 147.
[61] There were twenty-three circuits in operation in 1891. See Queen Mab, "Reports on the Postal Club Boxes – XI," *American Monthly Microscopical Journal* 12, no. 1 (1891): 13-14.
[62] See Romyn Hitchcock, "Notes," *American Monthly Microscopical Journal* 1, no. 1 (1880): 17-18.
[63] Dodge, "Editorial Pencillings," 147.
[64] List of members, circuits and officers of the Postal Microscopical Club for 1876, Collection 67, Papers of the American Postal Microscopical Club, Archives of the Academy of Natural Sciences, Philadelphia PA, USA. Hereafter list of members, 1876.

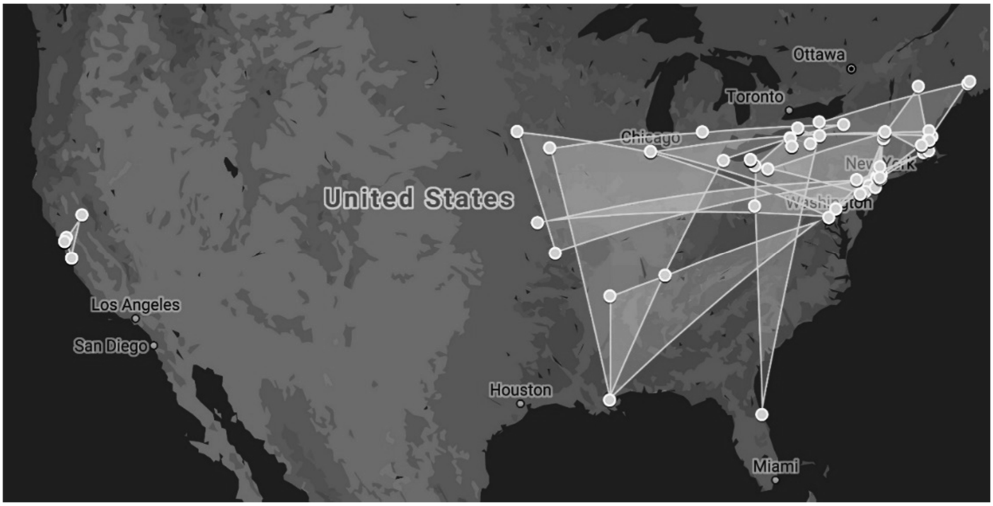

Figure 3.4 Intercity circuits of the American Postal Microscopical Club, 1876. Map data: Google, INEGI.

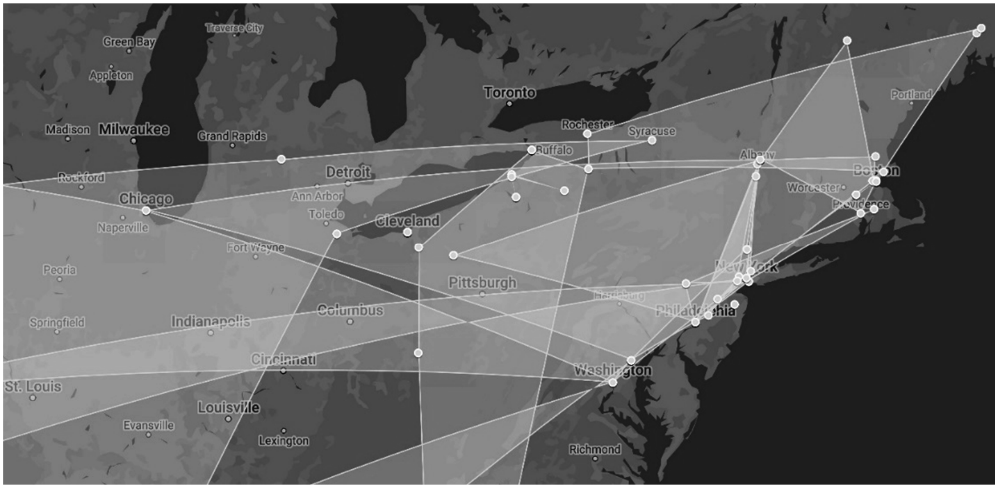

Figure 3.5 Close-up of intercity circuits on the Northeast coast, 1876. Map data: Google, INEGI.

The first officers of the club – the president, secretary and two managers – were John Peirce, Alpheus B. Hervey, Richard H. Ward and Charles M. Vorce.[65] Peirce was professor of chemistry at Harvard and Yale, Hervey taught theology and natural history at St. Lawrence University. Ward was a practicing physician and professor of botany at Rensselaer Polytechnic Institute, the first polytechnic in the United States, while Vorce was a patent lawyer who made microscope slides in his spare

[65] See list of members, 1876.

time. The officers are a fair sample of the members of the club in 1876, almost half of whom were either professors, physicians or clergymen.[66] When the club was founded, both Ward and Hervey were based in Troy, New York, which was made the headquarters of the club. Thus, Troy, at the time a wealthy industrial city and home to Rensselaer, became the central node in the postal network. Five of the club's circuits passed through Troy, more than through any other city (Fig. 3.4 and 3.5, near Albany).

There were concerns, however, that the club was less successful in making its slides available to microscopists located outside the scientific and industrial centres. The *Field and Forest* observed that many of the club's circuits were local, "no less than three circuits being located at Cleveland, Ohio, two at San Francisco, California, two at Boston and suburbs, one at New York City, and one mostly from its suburbs."[67] Yet there is evidence that the club did keep its promise of providing more isolated workers with slides. While most circuits established by 1876 cumulated along the Northeast coast, some did stretch to the South and Midwest, and there was one intercity circuit on the West Coast. In 1900, an anonymous member thanked the club, saying those "who live in the East do not appreciate how valuable the boxes of slides are to those of us who are farther removed from contact with the best scientific work."[68] Looking at the distribution of circuits shown in the map below (Fig. 3.4), it becomes clear that although the club reached beyond the centres of scientific research, members residing in the industrial cities along the East Coast and in the Great Lakes region continued to dominate the club's postal exchange.

Both the American Postal Microscopical Club and the British Postal Microscopical Society relied on the postal system to function, but in the case of the British society its dependence on the post, and sometimes the whims of individual postal workers, is less well documented. In 1887, J. W. Measures, the president of the British Postal Microscopical Society, recalled that there had been frequent breakages of slides in the early days of the society, but according to him, the introduction of the parcel post in 1883 had practically eliminated breakages.[69] Since the *Journal of the Postal Microscopical Society* was only established in 1882, there is little evidence of the society's early struggles to ensure the safe transmission of slides. In the United States, however, the domestic parcel post was only introduced in 1913. In the late nineteenth century, the US Post Office only carried parcels weighing four pounds or under and was known for its rather rough treatment of

[66] According to John Warner, 26% of the members were physicians, 11% professors, 8% clergymen. Warner, "'Exploring the Inner Labyrinths of Creation'," 17.
[67] See Dodge, "Editorial Pencillings."
[68] Richard H. Ward, "Report of the American Postal Microscopical Club," *American Monthly Microscopical Journal* 21, no. 3 (1900): 85.
[69] See J. W. Measures, "Presidential Address," *The Journal of the Postal Microscopical Society* 6 (1887): 1-7.

parcels during transit. Any parcels weighing more than four pounds were shipped by privately owned companies, which varied considerably in terms of their reliability and shipment rates. Moreover, while the US post expanded rapidly after the Civil War, the American postal law initially prohibited the mailing of glass, including microscope slides. For all these reasons, maintaining a smooth circulation of slides remained a matter of concern for some time in the United States and was well documented in the periodicals which reported on the activities of the American Postal Microscopical Club. The rest of this section, therefore, turns to the American Postal Microscopical Club, examining how the post shaped the club's circulation of slides, and vice versa.

As the historian Cameron Blevins writes, the US post expanded at an astounding pace after the Civil War, spurring the colonisation and integration of the West into the rest of the nation.[70] Blevins argues that the sprawling postal network was only partly dependent on the expansion of material infrastructures, such as roads and railways. Much like the two postal microscopy societies, the post itself depended on the organisation of people, using "a system of commissions, fees, and contracts to graft public functions onto the private operations of storeowners and stagecoach companies," and creating, in Blevins terms, a malleable "gossamer network."[71] The flexibility of this network, together with a long tradition of government support for the distribution of educational materials through the post, made it possible for microscopists to tailor the post to their needs.[72]

When the American Postal Microscopical Club was founded in 1875, the American postal law technically prohibited the mailing of glass, including microscope slides. The *United States Official Postal Guide* of 1876 elaborated that packages "containing liquids, poisons, glass, explosive chemicals, live animals, sharp pointed instruments, sugar, or any other matter liable to deface or destroy the contents of the mail, or injure the person of anyone connected with the service" could not be sent through the post.[73] The club therefore depended on the lenience of post office clerks, who usually did not consider the slides unsafe and allowed them to be sent.[74] Before the club was established, its officers had been assured by members of Congress that a future revision of the postal law would consider the needs of the club and allow for the mailing of slides.[75] But over the three years following

[70] See Cameron Blevins, "The Postal West: Spatial Integration and the American West, 1865-1902" (PhD dissertation, Stanford University, 2015). Blevins elaborates this argument in his recent book, *Paper Trails: The US Post and the Making of the American West* (New York: Oxford University Press, 2021).
[71] Blevins, "The Postal West," iv.
[72] Richard John emphasises the educational rationale underlying the establishment of the American postal system. John, *Spreading the News*, 30.
[73] "Rates of Postage on Domestic Mail-Matter," *United States Official Postal Guide* 1, no. 9 (1876): 18.
[74] See Richard H. Ward, "Annual Address of President R. H. Ward," *Proceedings of the American Society of Microscopists* 1 (1880): 35-51.
[75] See Ward, "Annual Address of President R. H. Ward."

the foundation of the club, incidents of slides being confiscated by the post increased, which ultimately forced the club to suspend its circulation of slides.[76]

Moreover, from the mid-1870s, the United States Post Office Department faced a growing debate over the classification of mail, which revolved around the question of which printed materials should be considered of public interest and therefore qualify for reduced postal rates.[77] In 1878, the law division of the Post Office Department, represented by Arthur H. Bissell, conferred with a number of East Coast publishers to discuss a revision of the classification system.[78] As microscopists saw it, the focus on print in the proposed revision of the postal law disregarded the needs of their postal club. They argued that, considering the club's commitment to scientific education, it was in the public interest to support microscopists in exchanging microscope slides, too, and not only printed matter. The seemingly biased revision of the postal law advocated by Bissell and the publishers, combined with the stricter enforcement of the ban on glass, were met with protest by microscopists.

John Phin, editor of *The American Journal of Microscopy and Popular Science*, published a scathing editorial in March 1878, "A new postal law for the discouragement of science." Phin found it intolerable that the delivery of slides depended on the goodwill of individual post office clerks, and he complained about the bias towards print in the classification of mail. He went so far as to turn the club's plea for a lift of the ban on glass into a more general argument about the value of objects in scientific education:

> [Why] should seeds, specimens for scientific study, or samples of goods, be charged more than *Missionary Heralds*, *Atlantic Monthlies*, or *Golden Rules*? Do not flowers exert as elevating an influence as Boston transcendentalism? Do not scientific exchanges and specimens promote the diffusion of knowledge quite as much as *Journals of Education*?[79]

Phin's article was a rhetorical blow to the proposed changes to the postal law. It made a case for considering tradespeople and their commodities – "seeds, specimens for scientific study, or samples of goods" – as equally important as theoretical literature in educating the American people on scientific methods. At the same time, however, Phin glossed over the irony that the officers of the Postal Microscopical Club never grew tired of reminding members to send explanatory texts

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[76] See Ward, "Annual Address of President R. H. Ward."

[77] See Richard B. Kielbowicz, "A History of Mail Classification and Its Underlying Policies and Purposes" (paper presented at the Postal Rate Commission's Mail Reclassification Proceeding, MC95-1, 1995).

[78] See Kielbowicz, "A History of Mail Classification." Kielbowicz writes that Bissell met with "representatives from *Scribner's Monthly*, *Christian Union*, *The Grocer*, *American News Company*, *The New York Times*, and Harper's magazine and book publishing house," 40.

[79] John Phin, "A New Postal Law for the Discouragement of Science," *The American Journal of Microscopy and Popular Science* 3, no. 3 (1878): 63-64.

along with their preparations. Slides without notes, as they saw it, were quite useless.[80]

A month later, Phin's polemic was given more political weight by a petition presented to the Senate by members of the Postal Microscopical Club, asking for a revision of the postal law to the advantage of the club.[81] For a long time, petitions had been a primary way for settler communities to integrate themselves in the nation's postal network and adapt its postal services to their needs.[82] Since the passage of the Post Office Act of 1792, establishing the United States Post Office Department, Congress had been flooded with petitions asking for mail routes to be expanded and post offices to be set up in even the most remote communities.[83] Since the expansion of the post was widely regarded as an invaluable means of building a nation and educating its citizens, petitions had considerable support among members of Congress and were hardly ever denied.[84] Moreover, as Blevins points out in describing the post as a gossamer network, new postal infrastructure was swiftly grafted onto existing structures, with general stores being turned into post offices and private stagecoach companies being contracted to work as postal carriers.[85]

It seems that the American Postal Microscopical Club benefited from Congress's long-standing inclination to grant petitions and adapt the nation's postal services accordingly. The petition submitted by the club in 1878 was successful. In 1879, at the first meeting of the American Society of Microscopists, Richard Ward reported that the postal law had been amended to allow for the mailing of slides, and that the club had resumed its circulation of preparations.[86] Although there was no reduction of postage for microscope slides, they could now be circulated on the condition that they were carefully wrapped and put into sturdy (and expensive) boxes before they were mailed. This was practicable for the club, but some members, fearing the additional expense, continued to look for another "method for … safe transmission" to maintain their private exchanges of slides and slide making businesses.[87]

While the amendment of the postal law allowed for the continuation of the club, it did not put an end to debates over how microscope slides were treated by the post. It did, however, mark the end of the club's attempts at changing the postal system by law. From the 1880s, the club's efforts at making preparation methods

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[80] Complaints about slides lacking notes were published in various microscopy journals, see, for example, Queen Mab, "Report on the Postal Club Boxes – V," *The American Monthly Microscopical Journal* 10 (1889): 85-86.
[81] See US Congress, *Congressional Record: Containing the Proceedings and Debates of the Forty-Fifth Congress, Second Session*, vol. 7 (Washington, DC: Government Printing Office, 1878), 2558.
[82] See Blevins, "The Postal West," 174.
[83] See John, *Spreading the News*, 50.
[84] Ibid.
[85] See Blevins, "The Postal West," 206.
[86] See Ward, "Annual Address of President R. H. Ward."
[87] Booth, "Breakage of Slides in the Mail," 38.

travel were directed more towards choosing the right materials to make and send microscope slides. Whereas this section has traced the origins of the two postal microscopy organisations, looking at how they were established and, in the case of the American Postal Microscopical Club, developed together with the post, the following section turns to the members' production of slides, investigating how the postal exchange of permanent slides made it possible for microscopists to learn how to make them.

Fragile Preparations

The original collections of slides of the two postal societies do not seem to exist anymore. However, beginning in 1884, the American Postal Microscopical Club added commercial slides to its boxes, which were produced by the English slide maker Arthur C. Cole. Since Cole's slides were widely distributed through a subscription service in Britain and abroad, copies of the slides still exist, and they can be used to illustrate the kind of skills slide making required. Cole provided his subscribers not only with weekly deliveries of slides, but also with texts and illustrations describing the slides and their preparation, as well as bibliographies of works dealing with the specimens his slides contained. These texts and illustrations, too, were circulated by the American Postal Microscopical Club. Taken together, Cole's slides, texts and illustrations were meant to serve as a model of fine craftsmanship and thorough description for club members to imitate.[88] Since Cole himself was a member of the British Postal Microscopical Society, it is safe to assume that members of the British society received his slides too.

In 1889, the members of the American club received a slide by Cole containing a section of a leaf of *Rhododendron ponticum*, accompanied by a text describing the species and a lithograph (Fig. 3.6 and 3.7). The rhododendron leaf, as the *American Monthly Microscopical Journal* reported, "was decolorized in alcohol previous to cutting, was stained with logwood, and mounted in Canada balsam."[89] The slide demonstrates that turning a microscope specimen into a permanent preparation asked for a whole range of skills: cutting and staining sections, choosing (and often making) a suitable mounting medium like Canada balsam, and sealing the slide with a ring of cement and cover glass. Even when the specimens were not cut or stained, mounting them could be challenging. As arrangers of diatoms, a group of microalgae, knew too well, mounting microorganisms on a slide was precision work: using a sharpened horse hair to pick them up, diatoms were carefully placed on a slide coated with shellac, which was then gently heated

[88] See Queen Mab, "Report Upon the Postal Club Boxes – III," *American Monthly Microscopical Journal* 10, no. 2 (1889): 33-34.
[89] Queen Mab, "Report Upon the Postal Club Boxes – II," *American Monthly Microscopical Journal* 10, no. 1 (1889): 7.

to fix the specimens. After that, the algae were usually covered with a mixture of Canada balsam and monobromonaphthalene, before the slide was sealed. The German slide maker Johann Diedrich Möller estimated that it took him forty days to make one slide containing 4,026 diatom specimens.[90]

Figure 3.6 Slide of *Rhododendron ponticum* made by Arthur C. Cole, distributed along with his *Studies in Microscopical Science*, Vol. 1, 1883. Image courtesy of Steve Gill.

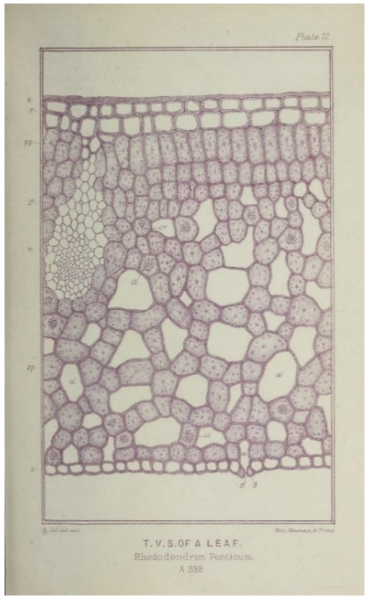

Figure 3.7 Illustration of *Rhododendron ponticum* in Arthur C. Coles *Studies of Microscopical Science*, Vol. 1, 1883. Image from the Biodiversity Heritage Library, contributed by the University of Illinois Urbana–Champaign.

Many of Cole's weekly deliveries included extensive manuals on how to cut, stain and mount specimens. However, the notes taken and circulated by the members who received his slides show that in order to learn how to make slides, it was necessary for microscopists to complement Cole's written instructions with a close observation of slides and illustrations. As the illustrator and member of the British postal society Tuffen West put it, microscopists had to "learn to read a slide like a book."[91] The historian Pamela Smith, in her work on early modern artisanal workshops, describes craft knowledge as empirical, "employing observation, precision

[90] See Johann Diedrich Möller, *Verzeichnis der in den Lichtdrucktafeln Möller'scher Diatomaceen-Präparate enthaltenen Arten* (Wedel: Selbstverlag des Herausgebers, 1892).
[91] Tuffen West, "Half-an-Hour at the Microscope," *The Journal of Microscopy and Natural Science* 6 (1887): 53.

and investigative experimentation."[92] Smith primarily refers to the close observation of natural phenomena, as well as experiments with working materials that informed artisanal crafts. Members of the postal club and society carefully observed the slides they received, with notetaking and sketch-making practices becoming a way of acquiring the craft knowledge that resided in the slides.

Since members of the postal club and society could keep a box of slides for only a few days, notes and illustrations helped to virtually extend the time spent with the slides. When a slide was damaged and sent to the headquarters for repairs, illustrations made by members came to replace the missing slide and were just as carefully observed. Building on Omar Nasim's work, the previous chapter has argued that observation itself was a craft that could only be learned through illustration and note-taking practices.[93] Scientific sketches were "working images," a way of observing an object by hand.[94] In a similar way, microscopists' observing by hand, through notes and sketches, was crucial in acquiring craft knowledge of preparation and mounting methods. Eugene A. Rau, a member of the American Postal Microscopical Club and apothecary from Bethlehem, Pennsylvania, frequently copied other members' notes and illustrations by hand and sketched what he saw when he examined a slide through the microscope.[95] Rau's notes thus make it possible for us to reconstruct how the club's slides were received and used by its members.

By exchanging drawings and notes alongside the slide boxes, the members both recorded successful methods and identified sources of error. Rau copied recommended recipes for mounting fluids and sketched features of specimens that struck him as particularly well prepared, indicating the effect of stains in his private notes and adding approving comments to them, "fine" or "very fine slide."[96] In January 1882, Rau received a box that contained a preparation made by Thomas Taylor, who was head of the Microscopy Division at the United States Department of Agriculture. Taylor had contributed a slide showing the foot of a fly, but he was concerned that it looked nothing like the one in Philip Henry Gosse's 1859 book *Evenings at the Microscope*. Taylor suspected that Gosse was at fault, but other members were quick to explain that Taylor had "evidently had all the pad & hairs torn away in the process [of preparation]" and suggested other methods that might lead to better results.[97]

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[92] Smith, "In a Sixteenth-Century Goldsmith's Workshop," 42.
[93] See Nasim, *Observing by Hand*. Lorraine Daston makes the similar argument that "taking notes entails taking note." Lorraine Daston, "Taking Note(s)," *Isis* 95, no. 3 (2004): 445.
[94] Nasim, *Observing by Hand*, 10.
[95] Eugene A. Rau's Floral Diary, also a list of slides & remarks upon objects sent through the Micro-Cabinet
Club, 1875–1887, Collection 67, Papers of the American Postal Microscopical Club, Archives of the Academy of Natural Sciences, Philadelphia, PA, USA. Hereafter Rau (1875–87).
[96] See Rau (1875-1887).
[97] See Rau (1875-1887).

Crushed specimens were often the result of applying too much pressure or using a blunt knife, whereas sections that were too thick at one end and too thin at the other had probably been cut by hand and not with a microtome. Observing both slides and illustrations by hand, microscopists learned to look out for visual hints of why a method had not worked. Rau even included meticulous sketches of broken slides in his notes, noting that these breakages were probably the result of improper packaging.[98] This kind of reverse engineering had a long tradition in microscopy, with microscopists perpetuating the myth that Canada balsam had only become popular after a microscopist "'smelt' his way" to the secret ingredient – resin of the balsam fir – used by a slide maker.[99] Members of the American Postal Microscopical Club were similarly eager to find out why someone's method had failed to deliver satisfying results. In fact, although the officers of the club asked members for their best preparations, the members found that failed preparations were often more instructive. An anonymous microscopist explained, "[there] is most interest in home-made slides, even if they are not pretty; the mounter learns so much more about the object, and he can explain its preparation so much better."[100]

Sven Dupré, in studying early modern recipe books, observes that in the seventeenth century, authors began to spell out sources of error and how to avoid them, a process Dupré terms the "codification of error."[101] Dupré describes the codification of error as a means of better translating craft knowledge into text, telling readers not only how to, but also how not to proceed in following a recipe. Jutta Schickore, looking at eighteenth-century microscopy publications, confirms that microscopists, too, discussed sources of error and whether to attribute them to the microscope or the observer.[102] While the reverse engineering undertaken by members of the American Postal Microscopical Club continued this tradition, members identified error not only by following, or failing to follow, someone else's instructions, but by closely observing another microscopist's slides. Since the slides were fragile but mobile objects and were circulated alongside written notes, the club made it possible for microscopists to judge both artisanal instructions and their execution.

Methodological debates could not always be settled as swiftly as in the case of Taylor's crushed foot of a fly. Many of the methods employed by club members were highly controversial, like the use of zinc white cement for gluing the cover glass onto a slide. Zinc white was notorious for spilling into a mount before it was

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[98] See Rau (1875–1887).

[99] Hitchcock, "Mounts and Mounting," 149. In a similar vein, microscopists fondly recalled the resourcefulness of John Thomas Quekett, one of the founders of the Royal Microscopical Society, who had famously repurposed various household items to build a working microscope. See A. D. Michael, "The President's Address," *Journal of the Royal Microscopical Society* 15, no. 1 (1895): 1-20.

[100] Ward, "Report of the American Postal Microscopical Club," 85-86.

[101] See Dupré, "Doing It Wrong."

[102] See Schickore, *The Microscope and the Eye*.

dry and becoming brittle once it had dried. One member quipped, “if it don’t [run], then it is because it has been appropriately thrown out of the window.”[103] Others, however, defended zinc white on the basis that its quality depended entirely on the skill of the person who made it, the particular ingredients used, and even local climatic conditions. Adapting preparation methods to a members’ local climate was a general challenge and discussed more than once in both the British and American organisation. For example, in 1882, an anonymous member of the British Postal Microscopical Society, who was about to leave for India, asked their fellow microscopists for mounting methods compatible with tropical climates.[104]

Pamela Smith has shown that early modern craft knowledge was particularistic, in that it could easily be adapted to local materials and environments. As Smith puts it, artisanal knowledge “necessitated playing off and employing the particularities of materials (including, in some cases, the impurities in the material).”[105] Caitlin Wylie makes the similar argument that present-day fossil preparators “value choosing among many possible techniques, preferring to use ‘what works’ for each particular fossil rather than a universal protocol.”[106] The preparation methods of late-nineteenth-century microscopists were equally flexible, and microscopists often agreed to disagree over the benefits and drawbacks of methods and materials, even when it came to the zinc white cement.[107] As the *American Monthly Microscopical Journal* wrote in a report on the club’s slides in 1889, “so often do authorities disagree ... that it is impossible for the individual worker implicitly to follow any set of rules. There is ample room for the development of the individuality and skill of every worker.”[108] At the same time, however, members observed that some slides were likely to be harmed, or harm others, during their travels, and they began to investigate spills and breakages.

There is reason to assume that in the slide exchange of the American Postal Microscopical Club breakages occurred quite regularly. Rau kept a register of the boxes he received between April 1884 and February 1886. In 1884, seventeen boxes – probably containing six slides each – contained only one broken cover glass. In 1885, he was sent thirteen boxes of slides containing one mended slide and one slide damaged beyond repair. 1886 started with three broken slides in three boxes.[109] Twice, mail bags containing one of the club’s slide boxes were run over

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[103] Richard H. Ward, "Sixteenth Annual Report of the American Postal Microscopical Club," *American Monthly Microscopical Journal* 12, no. 2 (1891): 59.
[104] See Alfred Allen, "[Editorial Note]," *The Journal of the Postal Microscopical Society* 1 (1882): 108.
[105] Smith, "In a Sixteenth-Century Goldsmith's Workshop," 43.
[106] Caitlin Donahue Wylie, *Preparing Dinosaurs: The Work Behind the Scenes* (Cambridge, MA.: MIT Press, 2021), 47.
[107] One member, Mary Ann Booth, made a conciliatory proposal in 1887, writing that although she preferred to use zinc white herself, less experienced microscopists might find King’s cement more useful. Mary Ann Booth, "A Thoroughly Reliable Cement," *The Microscope* 7, no. 10 (1887): 297-298.
[108] Queen Mab, "Report Upon the Postal Club Boxes – VII," *American Monthly Microscopical Journal* 10, no. 6 (1889): 132.
[109] See Rau (1875–1887).

by trains.[110] But even without such dramatic events, slides suffered from their two-year journey through the mails. A correspondent writing to the *American Monthly Microscopical Journal* suspected that heavy packages and careless postal workers were to blame:

> [Ordinary] mail packages are limited to four pounds in weight; but public documents passing through the mails are not restricted within any given limits … Glass slides can scarcely be expected to withstand such missiles, when the mail bags are hurled from the mail wagons upon stone sidewalks, or from postal cars to the platform … Does not some over-zealous post-office official open the boxes, as he has a perfect right to do, … [and] replace the slides with cells in contact, and packing half left out?[111]

British microscopists also occasionally reported on damaged slides, but J. W. Measures, president of the British Postal Microscopical society, asserted in 1887 that the establishment of the parcel post in 1883, together with the use of sturdy boxes, had almost eliminated breakages.[112] Still, the preparation methods of both American and British members were often chosen for their ability to withstand the test of postal exchange. Members were advised not to make dry mounts or water mounts, and not to use materials that were likely to be damaged themselves or damage other slides.

In March 1889, the *American Monthly Microscopical Journal* suggested "to have with each box the date when placed in circulation, thus affording, to some extent, a test of the comparative durability of the various modes of preparation."[113] This suggestion was taken up only three months later. The British Postal Microscopical Society also took some interest in the topic, publishing a report by a slide collector who studied the effect of his travels of 15,000-20,000 miles on his slides.[114] The club and society thus turned the circulation of slides into a long-term experiment to compare the durability of certain materials. This once more confirms Pamela Smith's argument that craft knowledge emerges through empirical observation: in the case of the American Postal Microscopical Club the postal exchange network itself, and its effect on the slides, became microscopists' object of study.

While preparations were privately evaluated by every microscopist through whose hands they passed, it could easily take two years for written comments to circle back to the maker of a preparation, if they made it back at all. In 1883, therefore, members of the British society agreed to change their rules and

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[110] See Richard H. Ward, "Extract from Report of Management of the American Postal Microscopical Club for 1893-1895," *American Monthly Microscopical Journal* 16, no. 4 (1895): 105-111.
[111] Booth, "Breakage of Slides in the Mail," 38.
[112] See Measures, "Presidential Address."
[113] Queen Mab, "Report Upon the Postal Club Boxes – IV," *American Monthly Microscopical Journal* 10, no. 3 (1889): 63.
[114] See H. N. Lyon, "Cements, Varnishes, and Cells," *The Journal of Microscopy and Natural Science* 8 (1889): 244-249.

have all notes pertaining to a slide sent to its maker at regular intervals. However, the officers of the American Postal Microscopical Society, after trying to return all notes to the contributor of a slide, decided to send "only the really important notes to the persons directly interested."[115] The officers soon realised that publishing the club's notes in microscopy periodicals made it possible to give advice to a slide maker and at the same time publicly assess the preparations circulated. Public judgement about the quality of artisanal products was a crucial component of craft knowledge, helping to determine what was considered good practice. In early modern times, an artisan's commissioned work often had to be publicly judged by other knowledgeable craftspeople before the artisan was paid the full fee by the commissioner.[116] In the case of late-nineteenth-century postal microscopy societies, reports on their activities published in various periodicals became the key site for public scrutiny.

The Postal Club and Society in the Periodical Press

After *Science Gossip* had helped to bring the British Postal Microscopical Society to life in 1873, the periodical sporadically reported on the activities of the society. But it was only in 1882, when the society began to issue its own journal, that its activities received broad and regular coverage. *The Journal of the Postal Microscopical Society* was the brainchild of Alfred Allen, co-founder of the society, who became editor and publisher of the periodical and often drew on his own savings to keep it afloat. Allen, as Brock has shown, became "more and more ambitious" in his publishing endeavours, increasing the pages of the journal more than once, and turning the quarterly journal into a monthly publication in 1891.[117] Allen's ambition was also reflected in the changing title of the journal. *The Journal of the Postal Microscopical Society* became *The Journal of Microscopy and Natural Science* in 1884, and *The International Journal of Microscopy and Natural Science* in 1891. In 1897, however, Allen admitted defeat. The journal still did not pay for itself and since Allen did not dare go into any more debt, it ceased publication. In the volatile nineteenth-century periodical market it was not uncommon for periodicals to be short-lived, especially if their success was tied to the fate of the editor.[118]

For as long as it existed, however, the journal was an integral part of the postal society and much valued by its members, even if they did not always express

[115] Richard H. Ward, "Seventeenth Annual Report of the American Postal Microscopical Club, Troy, N.Y., 1892," *The Microscope* 12, no. 9 (1892): 190.
[116] See Smith, "In a Sixteenth-Century Goldsmith's Workshop."
[117] See Brock, "Patronage and Publishing."
[118] Another example is the journal of the RMS experiencing several crises in the 1870s caused by the death of an editor and a publisher, and the bankruptcy of another publisher. See Brock, "Patronage and Publishing."

their recognition in monetary terms. The journal printed excerpts from the notebooks circulated among members, the annual presidential addresses, as well as articles dealing with microscopy and natural history more broadly. Notably, the journal published several long-lasting series of articles that came to shape the journal, as well as the members' skill in making microscope preparations: Tuffen West contributed reports on the slides he received, Vida Latham, an aspiring dentist, wrote a series of articles on cutting, staining and mounting techniques, while another member, William H. Burbidge, reviewed and compiled articles on microscopy for republication in Allen's journal.

Tuffen West's reports were entitled "Half-an-hour at the Microscope," a reference to Edwin Lankester's immensely popular 1859 book, *Half-hours with the Microscope*, which West had illustrated. Considering that West, as the previous chapter has shown, felt discontented with being credited as the illustrator and not the author of microscopy publications, authoring reports for Allen's journal must have been a welcome change. In his reports, West commented on the preparation of the slides he received, provided his readers with information on the specimens they contained, and he interspersed his writing with personal memories of his own encounters with some of these specimens during countryside rambles. Illustrator that he was, West sketched what he saw under the microscope and had his drawings published alongside his reports. Moreover, in order to learn how to make preparations, West regarded it as crucial to emulate the practices of more established, physical societies as much as possible. For example, he recommended to examine the slide boxes if not at society meetings, then at least together with friends. In 1875, seven years before *The Journal of the Postal Microscopical Society* was established, he explained:

> In other societies, on a member bringing forward a specimen, he enters into a description of it, with more or less detail: how it was obtained, and where; how prepared; draws attention to the peculiarities of structure presented; their adaptations; the observed connections with related objects; notes follow on anything of interest and mode of life; finally, sketches are presented, which in all well-regulated societies eventually make their appearance in 'Proceedings' or 'Transactions' for permanent record of work done … The more nearly our proceedings approach to those of other societies, the more stable and satisfactory will be our progress.[119]

In addition to giving microscopists an opportunity to re-enact society practices in print, Allen's journal invited knowledgeable mounters of specimens to describe their methods in detail. Starting in 1885, Vida Latham contributed a series of articles on preparation techniques. Latham, only nineteen or twenty years old at the

[119] Tuffen West, "Half-an-Hour at the Microscope," *The Journal of Microscopy and Natural Science* 3 (1894): 32.

time, went on to become a physician and dentist, advocating for a scientific approach to dentistry and for opening the field to women practitioners throughout her life. She became associate editor of Allen's journal sometime in the early 1890s. In her regular contributions to the journal, she explained how to make plant, animal and human preparations and did not spare her readers the gruesome details of injecting and cutting whole animals. It seems, therefore, that postal societies not only welcomed women to their ranks but also gave them an opportunity to divert in their writing from the "familiar format", which, as Lightman has argued, for a long time firmly placed women's scientific writing in the context of the family and domestic sphere.[120] Vida Latham also gave advice on how to practice mounting. As she saw it, documenting each step of the process was key, and she asked her readers "to note carefully the causes of each failure, and to take precautions to avoid these in … subsequent practice."[121] Latham evidently considered codifying error useful in tracking a mounter's personal progress.

Latham's articles on preparation techniques were complemented by a long-running series of articles on "Microscopical Technique" by an anonymous author, W. H. B., probably William H. Burbidge, a member of the British Postal Microscopical Society of whom little else is known. For each of his contributions, Burbidge compiled articles on preparation techniques which had appeared in other publications and had them reprinted in Allen's journal. Burbidge's compilations are interesting in so far as they echoed early modern methods of imparting craft knowledge through print. As Dupré has argued, early modern artisans, before they began to codify error in their writing in the seventeenth century, "seemed more interested in collecting various ways to arrive at the same or a similar result, than in sorting out the right ways from the wrong."[122] The "scissors-and-paste" practices that dominated much of the nineteenth-century periodical press afforded similar compilations of recipes.[123] Whereas preparers like West and Latham advised members of the postal society on how to, and how not to, make microscope slides based on their own experiences, Burbidge's compilations of articles offered them an overview of recent developments in mounting techniques but less personal guidance.

Bearing in mind that members like Tuffen West and Alfred Allen were convinced that their society needed its own periodical to thrive, it is surprising just how little the society's organisation of postal circuits depended on its journal. West's reports on the slides he received were not published at or around the time he examined them but, in some cases, years later. They did not help to track the

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[120] See Lightman, *Victorian Popularizers of Science*. To some extent, Mary Ward's *Microscope Teachings* continued the maternal tradition of science writing, see Chapter Two.
[121] Vida A. Latham, "The Microscope and How to Use It. Part VIII – Injecting," *The Journal of Microscopy and Natural Science* 6 (1887): 41.
[122] Dupré, "Doing It Wrong," 185.
[123] See Pigeon, "Steal It, Change It, Print It."

circulation of slides, nor did they help other members interpret the slides they received. Instead, society members primarily relied on the notes circulated to make sense of other members' preparations. As West suggested, the society's journal, just like other societies' transactions or proceedings, should be a "permanent record of work done."[124] Since the journal "aimed at a wider circulation than its [the postal society's] members," it was crucial that it contained information of more general interest.[125] Allen apparently decided that only some of the notes circulated were worth sharing with the readers of his journal. And if they were worth sharing in print, it was for the information on mounting they contained and not because they helped to track the circulation of slides. Allen's journal thus complemented the chain-letter network by sharing mounting instructions with society members, but its relation to the slide exchange was relatively loose. The journal rather aimed at institutionalising the British Postal Microscopical Society, proving that it was on a par with more established natural history societies in terms of the publications it produced, and offering subscribers who were not members of the society value for money, that is, articles which could be read independent of the circulation of slides.

This is in stark contrast to the American Postal Microscopical Club, which, not having its own journal, relied on multiple periodicals to keep its chain-letter circuits running. In the case of the American club, the complete lack of physical meetings, and the geographical dispersion of its members, acted as centrifugal forces that were difficult to contain and made it necessary to closely track the circulation of slides in the periodical press. Reports on the American Postal Microscopical Club were published regularly in the *American Quarterly Microscopical Journal* (1878–1902, from 1880 the *American Monthly Microscopical Journal*), *The American Journal of Microscopy and Popular Science* (1875–1881), *The Microscope* (1881–1897, then merged with the *American Monthly Microscopical Journal*), *The Journal of Applied Microscopy* (1898–1903), *The Microscopical Bulletin and Optician's Circular* (1883–1902, from 1885 *The Microscopical Bulletin and Science News*) and *The Observer* (1890–1895).[126] Of these six periodicals, none made it past 1903, which makes it difficult to trace the activities of the club after the turn of the century, or even determine when it ceased to exist.[127]

It is important to note that those microscopy periodicals did not address a homogeneous public. The contributors and readers of every periodical constituted a distinct audience, shaped by numerous factors from a journal's circulation to its

[124] West, "Half-an-Hour at the Microscope," 32.
[125] Brock, "Patronage and Publishing," 255.
[126] For an overview of nineteenth-century microscopy periodicals, see Brock, "Patronage and Publishing."
[127] Between 1903 and 1973, *Transactions of the American Microscopical Society* was the only microscopy periodical issued in North America. See Brock, "Patronage and Publishing," 260.

price, layout, content and materiality.[128] *The Microscopical Bulletin and Science News* and the short-lived *Journal of Applied Microscopy* were published by the scientific instrument makers James W. Queen & Co. and Bausch & Lomb, respectively. Whereas Bausch & Lomb's *Journal of Applied Microscopy*, a monthly priced at one dollar per annum, mainly reported on laboratories that the company had equipped with microscopes, *The Microscopical Bulletin and Science News* was a flimsy trade paper of eight pages, a bimonthly that ran on adverts and cost only twenty-five cents per year. *The American Quarterly Microscopical Journal* was initially published by the New York Microscopical Society and reported on society activities, whereas *The Microscope* started as a medical journal but was soon changed to cater to a broader and presumably larger readership, a similar readership as envisioned by John Phin's *American Journal of Microscopy and Popular Science*.[129] *The Observer*, finally, was a natural history journal with just a section dedicated to microscopy.

In short, the public gaze that the club's slides were subjected to was fragmented, and it was shaped by the various agendas of the periodicals. Moreover, readers looked at the slides through the eyes of the author, especially when the club's notes were not just reproduced or summarised in print but complemented by a report. Just like the periodical of the British Postal Microscopical Society, American microscopy periodicals chose knowledgeable members to write regular reports, who took different approaches to evaluating slides, as well as other members' knowledge of preparation methods. The two most prominent and regular commentators, who mainly wrote for the *American Monthly Microscopical Journal*, were Romyn Hitchcock and a writer who used the pen name Queen Mab.
Romyn Hitchcock was the long-time editor of the *American Monthly Microscopical Journal* and a prolific scientific writer, explorer and photographer with chemistry degrees from Cornell and Columbia. Hitchcock edited the *American Monthly Microscopical Journal* from 1878 to 1886, before joining the United States Eclipse Expedition and leaving for Japan the following year. In 1883, Hitchcock felt compelled to start reporting on the slides he received, since "some members who, while quite willing to avail themselves of the advantages of the club, [seemed] not to regard it as any part of their obligations as members to contribute to the general interest and value of the boxes."[130]

Hitchcock sought to remedy this by publicly assessing both the quality of slides and the reliability and moral integrity of their makers. Hitchcock held that members should "feel morally bound" to make valuable contributions to the

[128] See Margaret Beetham, "Towards a Theory of the Periodical as a Publishing Genre," in *Investigating Victorian Journalism*, ed. Laurel Brake, Aled Jones, and Lionel Madden (Basingstoke and London: Macmillan, 1990), 19–32.
[129] See Brock, "Patronage and Publishing."
[130] Romyn Hitchcock, "The American Postal Microscopical Club," *American Monthly Microscopical Journal* 4, no. 1 (1883): 14.

club.[131] From the early modern period, microscopists had promoted the notion that moral education could be gained by contemplating God's microscopic creatures through the microscope.[132] Hitchcock inverted this argument by claiming that, instead of refining their morals through microscopy, club members had to be trustworthy craftspeople and correspondents from the start. In order to make the club's infrastructure of slides and chain letters more robust, Hitchcock put club members under just as much public scrutiny as their preparation methods. In his reports, Hitchcock listed the names of all contributors to a box of slides and discussed their skill and reliability one by one. Whereas a beginner's ignorance was excusable, Hitchcock made it clear that carelessness was not, and he criticised even esteemed microscopists for contributing slides of low quality.

After Hitchcock left for Japan, the task of writing reports was taken over by an anonymous author whom the new editor of the *American Monthly Microscopical Journal*, Charles W. Smiley, christened "Queen Mab, one of the most skilful preparers of material in this country."[133] Judging by the pseudonym of the writer and the content of the reports, it is plausible to assume that Queen Mab was Mary Ann Booth, the best known female maker and seller of slides in the United States at the time, and a member of the Postal Microscopical Club since at least 1884.[134] Queen Mab made good use of her new role as public commentator, often adding more general directions for the club to her examination of slides.

In 1889, when a female member contributed a slide made by a male preparer, Queen Mab asked the ladies in the club to only circulate preparations they had made themselves and declared microscopy a female craft: "We cannot too warmly urge upon the attention of ladies the fascination and instruction to be found in the use of the microscope, a branch of science for which nature has especially adapted them both mentally and manually."[135] Describing women as naturally gifted for delicate craft work was a recurrent theme in other scientific fields, too, like botany, as Ann B. Shteir has shown.[136] Drawing on gendered views of craft,

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[131] Hitchcock, "The American Postal Microscopical Club," 14.

[132] See Jordynn Jack, "A Pedagogy of Sight: Microscopic Vision in Robert Hooke's Micrographia," *Quarterly Journal of Speech* 95, no. 2 (2009): 192-209. On nineteenth-century microscopy and theology, see Lightman, "Visual Theology;" Warner, "'Exploring the Inner Labyrinths of Creation'."

[133] Charles W. Smiley, "Editorial," *American Monthly Microscopical Journal* 10, no. 1 (1889): 17. In a footnote to the first report on the club, Smiley quotes Robert Herrick's (1591-1674) poem "The fairies", which describes Queen Mab as a fairy who enforces social mores by pinching sloppy housekeepers "in the toe". The reviewer Queen Mab had a similar role, ruling over a miniature world of microscope specimens and criticising careless slide makers. See Queen Mab, "Report Upon the Postal Club Boxes – I," *American Monthly Microscopical Journal* 9, no. 12 (1888): 224. Francesca Brittan investigates the relationship between microscopy and fairies in her "On Microscopic Hearing."

[134] "Mab" may have been an acronym of Mary Ann Booth's initials. Moreover, Booth was widely appreciated for her knowledge of human parasites and Queen Mab's reports contain long paragraphs about parasites and how to prepare them. Rau (1875–1887) mentions slides circulated by Booth in 1884, but she may have joined the club earlier.

[135] Queen Mab, "Report Upon the Postal Club Boxes – IV," 63.

[136] See Ann B. Shteir, "'Fac-Similes of Nature': Victorian Wax Flower Modelling," *Victorian Literature and Culture* 35, no. 2 (2007): 649-661.

Queen Mab's reports established who should be considered a knowledgeable craftsperson. Moreover, Queen Mab positioned club members' work as complementary to the kind of microscopy that was done in laboratories. She claimed that whereas "the preparation of certain classes of objects … reached a degree of perfection little short of marvellous" in laboratories, "the permanent preparation of objects … made no such advances."[137] Instead, she wrote, there was "an incongruity between skilful preparation and unskilful preservation," which club members could help overcome.[138]

Besides providing their readers with reviews, American microscopy periodicals also made it possible to centralise and synchronise club members' work. The historian Richard John has noted that the American post relied on newspaper reports to stay informed on any disruptions to the postal system that happened "in the field."[139] Likewise, members of the Postal Microscopical Club relied on periodicals to learn where their own slides had gone, which slides to expect in the next box, and find out if there had been delays. Published reports could also be used to give quick responses to queries made by club members. As Hitchcock explained in one of his reports in 1886:

> The preparer desires to know the name of the specimen. Such questions as this should receive answer in the letter-packet, although, for the information of the inquirer, the answers will be of little value, except through the medium of these notices … since those who once receive a box are not likely to see it again, these columns are always open for replies to such inquiries.[140]

Such exchanges among members were only possible with the help of a periodical, a genre James Mussell has defined as immutable across space, since an issue changed little as it was distributed, and mutable across time, with one issue always being replaced by the next.[141] Hitchcock's report shows that it was exactly this combination of mutability and immutability of periodicals that facilitated the collaboration among club members, making it possible for members to communicate with future recipients of slides and with their manufacturers.

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[137] Queen Mab, "Report Upon the Postal Club Boxes – IX," *American Monthly Microscopical Journal* 11, no. 1 (1890): 9.
[138] Ibid.
[139] John, *Spreading the News*, 76.
[140] Romyn Hitchcock, "Postal Club Boxes," *American Monthly Microscopical Journal* 7, no. 1 (1886): 17.
[141] See Mussell, *Science, Time and Space in the Late Nineteenth-Century Periodical Press: Movable Types*. For a comprehensive study of seriality in nineteenth-century science, see Nick Hopwood, Simon Schaffer, and Jim Secord, "Seriality and Scientific Objects in the Nineteenth Century," *History of Science* 48, no. 3/4 (2010): 251-285.

However, while microscopy periodicals certainly fostered a sense of community, sharing craft knowledge in published form remained a challenge.[142] As a trade paper, James W. Queen & Co.'s *Microscopical Bulletin and Science News* took an approach that made it stand out among the periodicals that reported on the club's slides. The *Microscopical Bulletin* was edited by Edward Pennock, an entrepreneur based in Philadelphia, who supervised the microscopy department at James W. Queen & Co. Pennock gave the bulletin a strong editorial voice, fashioning himself as a cunning tradesman with a dry sense of humour. Like Burbidge, who compiled articles for the journal of the British Postal Microscopical Society, Pennock often copied articles published in other journals and republished them in his bulletin, since he believed that he could "write much better articles with the scissors than with the pen."[143] For Pennock, writing was an editorial craft that required the hand as much as the mind.

Since the bulletin combined scientific news with price lists of items sold by James W. Queen & Co., its reports on the American Postal Microscopical Club became entangled with all sorts of microscopy accessories, ranging from microtomes to glass covers and stains. Claire Jones, in her work on medical trade catalogues in nineteenth- and twentieth-century Britain, has shown that catalogues were integral to medical and scientific practice. By the 1900s, catalogues contained "text relating products to medical practice and outlining their relation to medical theory."[144] Medical practitioners both ordered products and contributed their own designs for medical devices to trade catalogues, while the items and texts in these publications helped to foster the image of medicine as scientific and progressive.[145] Queen & Co.'s bulletin sought to bridge the gap between microscopy products and their application in a similar way. In its reports on the American Postal Microscopical Club, the bulletin pointed its readers to the tools that would enable them to follow the instructions circulated by club members.

In 1889, the *Microscopical Bulletin* published club members' notes on the Peirce Cell, a glass cell that could be used to contain dry mounts.[146] In a footnote to the report, the bulletin referred its readers to a description of the cell in the February 1886 issue. The 1886 article, including two illustrations, explained how the cell should be used and promised that Peirce Cells would soon be available at Queen & Co.[147] It offered its readers several recipes for cements they should use

[142] On periodicals and the building of scientific communities in the nineteenth century, see Leary, "A Victorian Virtual Community;" Belknap, "Illustrating Natural History;" Gowan Dawson et al., eds., *Science Periodicals in Nineteenth-Century Britain: Constructing Scientific Communities* (Chicago and London: University of Chicago Press, 2020).
[143] Edward Pennock, "Minutiae," *The Microscopical Bulletin and Science News* 7, no. 1 (1890): 7.
[144] Claire L. Jones, *The Medical Trade Catalogue in Britain, 1870–1914* (London: Routledge, 2016), 138.
[145] Jones, *The Medical Trade Catalogue in Britain, 1870–1914*, 150.
[146] See "American Postal Microscopical Club," *The Microscopical Bulletin and Science News* 6, no. 3 (1889): 18-19.
[147] See "The Peirce Cell for Opaques," *The Microscopical Bulletin and Science News* 3, no. 1 (1886): 3.

with the cell, thus effectively tailoring mounting methods to the items offered by Queen & Co. Although the bulletin could not quite recreate the collaborative experience of a physical workshop, it was crucial in bringing club members, mounting instructions and materials together. The August 1886 issue of the *Microscopical Bulletin* contained a correction of a cement recipe published in February, asking its readers to "strike out the words 'Make up only as needed' … as this cement becomes much more adhesive after having been made up for some time."[148] In the February issue held by the University of California, the words have been crossed out accordingly.[149] It was common for nineteenth-century periodicals to provide their readers with a list of errata to correct mistakes made in a previous issue. As Gowan Dawson has argued, the serial format of the science periodical made it possible for publishers to include corrections in later issues, instead of producing a new revised edition of an expensive scientific monograph.[150] The example of the revised cement recipe in the *Microscopical Bulletin* suggests that the serial format also enabled publishers to share and correct recipes as they changed through experience.

The two postal microscopy organisations thus not only relied on periodicals as public fora where mounting skills came under public scrutiny – the American club more than its British counterpart – but just as much on the material qualities of periodicals, their distribution in time and space, and, in the case of the British Postal Microscopical Society, the importance of periodicals in institutionalising an organisation whose members hardly ever got together in person. The periodical press made it possible for microscopists to assess others' craft knowledge of mounting, as well as their reliability in sharing slides with other members, track the circulation of slides, and give their organisations if not a physical meeting site, then at least a virtual home in the pages of periodicals.

Conclusion

The history of the British Postal Microscopical Society and the American Postal Microscopical Club shows that craft knowledge was generated at a distance through the knowledge infrastructures members of the postal club and society helped to build and maintain. To a large extent, the members' collaboration relied on chain-letter networks and, at least in the case of the American Postal Microscopical Club, the reports published in microscopy periodicals. And it was in the virtual forum of the periodical, too, that microscope slides came under public scrutiny. Craft knowledge of slide making thus came to be entwined with microscopists' skill in

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148 "Correction," *The Microscopical Bulletin and Science News* 3, no. 4 (1886): 31.
149 The issue has been digitised and can be accessed through the HathiTrust library.
150 Gowan Dawson, *Show Me the Bone: Reconstructing Prehistoric Monsters in Nineteenth-Century Britain and America* (Chicago: University of Chicago Press, 2016), 139.

navigating the expanding knowledge infrastructures of the late nineteenth century. In order to work with other club members, microscopists had to learn how to align (and adapt) the postal system, periodicals, and their knowledge of how to make durable slides. From its inception, the American Postal Microscopical Club depended on the American postal system, and actively changed it, as demonstrated by its successful 1878 petition. The amendment of the postal law laid the groundwork for a postal system that facilitated the mailing of scientific trade items. Over time, both the British and American chain-letter networks themselves became long-term experiments to test the durability of slides.

This chapter has also laid bare the strategies microscopists developed to learn how to make microscope slides without being able to meet and practice together. Learning how to prepare and mount specimens depended on the empirical observation of slides and illustrations, and their triangulation with written instructions. Like the observation of microscope specimens, the observation of slides was a craft in itself, with members observing materials by hand to understand why methods had succeeded or failed. While this demonstrates that craft knowledge was indeed, as Pamela Smith claims, empirical, it also suggests that one artisanal practice, observing by hand, could compensate for the lack of another collaborative practice, that is, learning how to prepare specimens together. The history of postal microscopy organisations also shows that we should pay more attention to how reverse engineering failure helped to acquire craft knowledge at a distance.

The serial format of microscopy periodicals helped to turn the production of slides into a collaborative and public endeavour. There are many examples of nineteenth-century societies extending their activities into the pages of periodicals and becoming, at least partly, virtual communities in the process. In the case of the American Postal Microscopical Club, microscopy periodicals faced the challenge of reporting on an organisation that was never more than virtual and needed published reports to function. James W. Queen & Co.'s *Microscopical Bulletin and Science News* matched the club's instructions with suitable tools, ingredients and tried recipes, assisting microscopists both in following the club's instructions and in their use of Queen & Co.'s products. The *American Monthly Microscopical Journal* helped to organise the chain-letter network by reporting on the location of slides, forwarding inquiries, and disciplining unreliable club members. To guarantee that the chain-letter system ran smoothly, the assessment of club members' individual skill and reliability became as important as the public judgement about the quality of slides.

The British Postal Microscopical Society was more connected to local, physical communities. It encouraged its members to meet in person and organised annual meetings. The society's journal – itself an attempt to emulate the practices of more established societies – did not so much coordinate the postal circuits but helped to institutionalise the postal organisation within the broader landscape of

British natural history societies. Whereas the American Postal Microscopical Club seems to disappear from the historical record around 1900, the British Postal Microscopical Society still exists today. It is tempting, therefore, to believe that the British society was the more successful of the two and that, in the long term, craft knowledge can be better acquired in communities that are more firmly rooted in place and only partly virtual. However, it is important to remember that many microscopists could not join more established, physical societies because they were women, disabled, or because they lived in remote places. For them, the question was not so much what the best way of learning how to make slides might be, but how to learn slide making at all, and, at least for a while, chain-letter networks helped tremendously with that.

Whereas this chapter has focused on a rather loose virtual community of microscopists connected mainly through chain-letters and periodicals, the following chapter turns to a group of microscopists which was more close-knit than the members of the two postal organisations. It looks at the collaboration between the German physicist Ernst Abbe, who was employed by the microscope manufacturer Carl Zeiss, and the Fellows of the RMS. Their collaboration was spurred by a controversy over the limit of microscopic vision and how to approach it in microscope objectives, a "battle of the glasses," as one contemporary called it. The chapter shows that industrial science – the production of microscopes at the Zeiss company – came to benefit both from the knowledge infrastructures built by the Fellows of the RMS and the "battle of the glasses."

4 Controversy and Innovation: Ernst Abbe, the RMS, and the "Battle of the Glasses"

> [The American microscope manufacturers] Spencer and Tolles . . . were perfecting their work, and the latter preparing to make an objective which was to become more famous, perhaps, than any other bit of glass ever was. I trust that it reposes safely in the cabinet of the Royal Microscopical Society, where it may for centuries be pointed out as the scientific instrument over which a great historic battle was waged.[1]

The "great historic battle" referred to by the president of the American Society of Microscopists, Jacob Cox, in the quote above was a controversy over the maximum aperture of immersion lenses and how to measure it. Aperture describes the ability of an objective lens to accept incoming light, which will be explained in more detail later in this chapter. Whereas dry lenses collect light travelling through the air surrounding the lens, immersion lenses are immersed in a medium with a higher refractive index than air, such as oil or water, which reduces the amount of light lost through refraction when light beams enter the lens. Some of the most prominent Fellows of the Royal Microscopical Society (RMS), above all the engineer Francis Wenham, were convinced that the angular aperture of an immersion lens could not possibly exceed 82°, and that an aperture greater than that would defy the laws of optics. However, an immersion lens constructed by the American microscope manufacturer Robert Tolles in 1871 challenged that belief, since its aperture exceeded the critical 82°.[2] Wenham deemed Tolles' lens a hoax and a controversy ensued that lasted roughly until the end of the decade.

Whereas the previous chapters were concerned with the kinds of infrastructure that made it possible for microscopists scattered across Great Britain and the United States to learn how to observe microscope specimens and make permanent microscope slides together, this chapter looks at how American, British, and German microscopists collaboratively innovated objective lenses during and after the "battle of the glasses" in the 1870s and 1880s. The previous two chapters have laid bare microscopists' knowledge infrastructures by tracking microscopy illustrations as they were copied and exchanged among microscopists, and by following the maintainers of postal microscopy societies, who kept the chain-letter exchange running by organising members into circuits, reporting on the circulation of slides, and disciplining unreliable correspondents if necessary. This chapter

[1] Jacob Cox, "Annual Address of the President: Robert H. Tolles and the Angular Aperture Question," *Proceedings of the American Society of Microscopists* 6 (1884): 6-7.
[2] Cox points out that the controversy was preceded by disagreements about the optical qualities of immersion lenses reaching back as far as the 1850s. For a prehistory of the controversy, see Cox, "Annual Address of the President."

adopts another approach outlined by Karasti and Blomberg to achieve infrastructural inversion. In addition to following material artefacts and the maintainers of infrastructure, we can also expose infrastructure by studying controversies. The two authors argue that during “breakdowns” of infrastructure, or “controversies,” the “work that keeps the infrastructure aligned becomes accessible to the researcher as actors provide explicit articulations of the controversy.”[3] Turning to the “battle of the glasses,” this chapter helps to answer the main research question of how craft knowledge of microscopy was shared by examining how commercial manufacturers like Zeiss and Abbe profited from the knowledge infrastructures established by the microscopy community.

Since the aperture of a lens affects its resolving power, with greater aperture generally leading to higher resolution, the controversy spurred by Robert Tolles' immersion lens revolved not only around the question of what the maximum aperture of an immersion lens was, but what the maximum resolution was that could be achieved with a light microscope. Consequently, the controversy fought over immersion lenses was tied to a broader debate over the ultimate limit of microscopic vision. Around the mid-nineteenth century, microscope manufacturers had made great strides in the construction of high-resolution objectives, making it possible to resolve exceedingly small microscope specimens, but by the 1870s it had become more difficult to increase the resolution of an objective significantly.[4] This made the question of what the ultimate limit of resolution was, and to what extent it had been achieved already, more pressing. In Wenham's view, the declared aperture (and resolution) of Tolles' lens were optically impossible – the aperture that was supposedly achieved with the lens was essentially too good to be true. The dynamic of the debate changed after the German physicists Hermann von Helmholtz and Ernst Abbe independently calculated the ultimate limit of microscopic vision in 1873, which proved Tolles correct. The Fellows of the Royal Microscopical Society who had been sceptical about Wenham's views for some time were curious to learn more about the theoretical limit of resolution and began a lively correspondence with Abbe.

When one of the Fellows, John Ware Stephenson, came to understand the implications of Abbe's theory for the design of microscopes, he sent multiple letters to both Abbe and his employer, the Jena-based microscope manufacturer Carl Zeiss, in 1876 and 1877. Stephenson asked them to build a “homogeneous” immersion lens with an immersion medium approaching the refractive index of the glass

[3] Karasti and Blomberg, "Studying Infrastructuring Ethnographically," 252.
[4] One reason for Abbe's 1876 visit to London was that he wanted to use a range of British microscopes and test his theory that improvements in microscopic vision could only be made through the development of new kinds of optical glass. See Ernst Abbe and Otto Schott, "Vorläufiger Bericht über eine wissenschaftliche Untersuchung zur Verbesserung des optischen Glases vom 30.III.82," in *Gesammelte Abhandlungen von Ernst Abbe*, ed. Moritz von Rohr (Hildesheim: Georg Olms, 1989), 1-26; Ernst Abbe, "Die optischen Hülfsmittel der Mikroskopie," in *Gesammelte Abhandlungen von Ernst Abbe*, ed. Siegfried Czapski (Hildesheim: Georg Olms, 1989), 119-164.

of the lens, which would further decrease the refracting surfaces and increase the resolution of the objective. At first, Abbe was quite unimpressed (and unresponsive) since he considered homogeneous immersion rather impractical for most microscopists and expensive to produce. As he pointed out to Stephenson, making homogeneous immersion lenses required so much skill that only one man in Zeiss' workshop was able to grind the lens, and another to make the fitting brass work.[5] Yet it seems that Stephenson eventually convinced Abbe of the wider applicability and scientific value of his invention – Zeiss started to produce homogeneous immersion lenses in 1877. German bacteriologists soon began to use the lenses and in 1878 Robert Koch declared that they had been crucial for his research into infectious diseases.[6] It quickly became evident that producing Stephenson's innovation would pay off. Thus, the controversy surrounding immersion lenses, and Stephenson's attempt to better understand aperture with the help of Abbe's theory, eventually facilitated the collaborative development of homogeneous immersion lenses.

Abbe's biographers have mainly portrayed his correspondence with the RMS as a teacher-student relationship. According to them, Abbe's 1873 theory of microscopic vision and its application to the production of microscopes sealed the descent of British microscopy and firmly shifted the centre of European microscopy from London to Jena. As a result, British microscopists began to turn to Abbe for instruction. Abbe, in turn, supposedly profited from his exchanges with the RMS Fellows by establishing an emotional bond with a community of fellow enthusiasts that he could not find among his own countrymen.[7] The letters exchanged between Abbe and the Fellows indeed suggest that Abbe found it personally rewarding to correspond with British microscopists because they shared his enthusiasm. However, describing their exchange as a one-way transfer of knowledge, with Abbe explaining his theory to the Fellows, does not do justice to the inventiveness of Abbe's correspondents and the wealth of resources they made available to him. Instead, drawing on Sam Alberti's work, this chapter argues that Abbe and his employer Zeiss benefitted from a wave of "amateurisation," which had transformed the British scientific landscape since the 1860s and helped to establish an early form of a user innovation community of microscopists. This community of microscopists and its knowledge infrastructures, including microscopy societies, periodicals, collections and concerted public demonstrations, became essential to the innovation of microscopes built by Zeiss in the late 1870s and 1880s.

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[5] Abbe, Ernst. Letter to John Ware Stephenson. 29 Dec. 1877. RMS Internal Archives.
[6] See Robert Koch, "Neue Untersuchungen über die Mikroorganismen bei infectiösen Wundkrankheiten," *Deutsche Medicinische Wochenschrift* 4, no. 43 (1878): 531-533.
[7] The two most comprehensive biographies of Ernst Abbe where this argument is made are Moritz von Rohr, *Ernst Abbe* (Jena: Gustav Fischer, 1940); Felix Auerbach, *Ernst Abbe: Sein Leben, sein Wirken, seine Persönlichkeit* (Leipzig: Akademische Verlagsgesellschaft, 1918).

On a theoretical level, this chapter brings innovation and controversy studies into closer conversation. Innovation studies scholars tend to conceive of tensions, or controversy, among innovating users as "creative abrasion," a clash of different experiences, kinds of expertise and approaches to problem solving that is part of the creative process.[8] But very few, if any, of these scholars fully acknowledge the power of controversies in reconfiguring the user innovation community, including its knowledge infrastructures. The notion of free exchanges among user innovators in a knowledge commons seems to prevail in the innovation studies literature, with tensions among users being rather minor hiccups in the innovation process. Scholars in science and technologies studies working on controversy, on the other hand, have researched controversies around emerging technologies but have spent little thought on how, vice versa, innovation springs from controversy.[9] Both bodies of literature offer rather few routes to better understand the mutual effects of scientific controversies and user innovation communities on the innovation process. Yet, as this chapter shows, where there is controversy, there is likely to be (user) innovation too. In following the different stages of the "battle of the glasses," the chapter shows that controversy both spurs user innovation and reconfigures the user innovation community and its knowledge infrastructures in the process.

The chapter first expands on the theoretical considerations underlying it, focusing on concepts of amateurisation and user innovation. Next, the chapter follows the two stages of the "battle of the glasses": the transatlantic exchange between Robert Tolles and Francis Wenham from 1871 onwards, and the shift to Europe after 1873, when Abbe's theory became the focus of the debate. The chapter looks at how infrastructures established through the amateurisation of British microscopy made it possible for Abbe and the RMS Fellows to innovate microscope lenses and other equipment together, but also how the controversy affected those infrastructures as it wore on.

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[8] The work most often cited on creative abrasion is Dorothy A. Leonard-Barton and Walter C. Swap, *When Sparks Fly: Igniting Creativity in Groups* (Boston, MA.: Harvard Business School Press, 1999). It seems worth pointing out that Alessia Contu has criticised Leonard-Barton and Swap's neglect of power dynamics in creative abrasion, which she considers a weakness of the organisational literature more generally. Contu provides a study of these power dynamics in Alessia Contu, "On Boundaries and Difference: Communities of Practice and Power Relations in Creative Work," *Management Learning* 45, no. 3 (2013): 289-316.

[9] Historical research into conflict around emerging technologies has, of course, looked at the role of users more broadly. See, for example, Wiebe E. Bijker, *Of Bicycles, Bakelites, and Bulbs: Toward a Theory of Sociotechnical Change* (Cambridge, MA: MIT Press, 1995); Ruth Oldenziel and Mikael Hård, *Consumers, Tinkerers, Rebels: The People Who Shaped Europe* (Basingstoke: Palgrave Macmillan UK, 2013).

Amateurisation and User Innovation

In the 1860s and 1870s, as the previous chapter has shown, the RMS was joined by many other microscopy societies and clubs across Britain – the first English translation of Abbe's 1873 work on microscopic vision was read at a meeting of the microscopical section of the Bristol Naturalist's Society.[10] The widespread emergence of field clubs and societies organised by and for non-professional researchers at the time has been described by Sam Alberti and others as a process of "amateurisation."[11] Just like emerging professional scientists working in laboratories, naturalists without formal scientific training wanted to establish a new identity for themselves. They "sought to replace the image of the lone naturalist collecting for aesthetic or other unsuitable ends with a new, rigorous, collective identity."[12] Science professionalisers like Thomas Huxley, benefitting from the rise of public interest in science, helped this development but were eager to frame the work done by researchers without formal training as merely supporting the cause of lab science. When Huxley was president of the Quekett Microscopical Club, he suggested that club members focus on "the following up of details, tracing out minutiae of structure," work "which certainly cannot be undertaken by those who have to occupy themselves with science as a whole."[13]

Although the RMS had already been founded in 1839, the process of amateurisation of the 1860s and 1870s left its mark on the society, as the RMS Fellows went to great lengths to, in Alberti's terms, "appear unified and effective."[14] It was only in the 1860s, for example, that the RMS collection of scientific instruments was founded and the society was granted a Royal Charter. In 1868, the RMS consisted of 452 Fellows, the highest membership recorded since its foundation. Two years later, the RMS president, Henry J. Slack, decided to give the first presidential address dedicated to a scientific topic, instead of recounting the activities of the society during the past year. A year later, in 1869, the RMS established its own independent journal, *The Monthly Microscopical Journal*. The journal soon adopted the practice of reporting on the activities of other microscopy societies, too, and in

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[10] See Brock, "Patronage and Publishing," 257.
[11] The concept is elaborated in Alberti, "Amateurs and Professionals in One County." Alberti draws on Lowe's work, where the term was used but not explained in much detail: Philip D. Lowe, "Locals and Cosmopolitans: A Model for the Social Organisation of Provincial Science in the Nineteenth Century" (MPhil thesis, Sussex University, 1978); Philip D. Lowe, "The British Association and the Provincial Public," in *The Parliament of Science: The British Association for the Advancement Ofscience*, ed. Roy MacLeod and Peter Collins (Northwood: Science Reviews, Ltd., 1981), 118–144.
[12] Alberti, "Amateurs and Professionals in One County," 133.
[13] Thomas H. Huxley, "The President's Address," *Journal of the Quekett Microscopical Club* 5 (1879): 253, 255.
[14] Alberti, "Amateurs and Professionals in One County," 133.

1879, the RMS decided to make the presidents of other societies ex-officio members "on the principle that co-operation with rivals is good policy."[15] As lists of members of the RMS and other societies show, microscopists who could afford it often joined more than one society. During the 1860s and 1870s, the RMS became a central node in an ever-denser network of British microscopy societies, which were linked through mutual reprints of society proceedings and scientific papers, agreements to exchange their periodicals on a regular basis, and overlapping memberships.

So far, studies of nineteenth-century amateurisation have focused on the rhetoric and scientific self-fashioning in the formation of a shared identity among local groups of amateurs.[16] This chapter, however, is not much concerned with amateurs' identity. Instead, it reframes amateurisation as the formation of large-scale infrastructures in 1860s' and 1870s' Britain which furthered the exchange of scientific information but also served as a testbed for the development of innovative technology. In acknowledging the rise of standardised methods through amateurisation, Alberti's study of amateurs in Yorkshire has already touched upon this larger infrastructural transformation. Scientific amateurs, as Alberti puts it, "were looking to eliminate the picnicking element and to standardize fieldwork methods."[17] The coordination of scattered fieldworkers and the standardisation of their methods were facilitated by microscopy clubs and societies, periodicals, and the sprawling postal system. In the case of microscopy, amateurisation was intertwined with the emergence of a community of innovative microscope users reaching across Britain and beyond.

In order to better understand and acknowledge the contribution British microscopists made to the innovation of microscopes at the Carl Zeiss company in Jena, it is useful to draw on the user innovation literature. Research into user innovation reaches back to the 1970s, when it was heralded by Eric von Hippel's 1976 paper on the role of users in innovating scientific instruments.[18] Von Hippel demonstrated that the vast majority of scientific instruments in his quantitative study were innovated by the scientists who used them and not their original manufacturers. Over the following decades, research into user innovation developed

[15] Gerard L'E. Turner, *God Bless the Microscope! A History of the Royal Microscopical Society over 150 Years* (Oxford: Royal Microscopical Society, 1989), 51.
[16] Alberti's work cited above focuses on the scientific self-fashioning of amateurs. Likewise, Matt Wale looks at various (rhetorical) strategies of amateurisation in the entomology community in Wale, "'The Sympathy of a Crowd'."
[17] Alberti, "Amateurs and Professionals in One County," 138.
[18] See Eric von Hippel, "The Dominant Role of Users in the Scientific Instrument Innovation Process," *Research Policy* 5, no. 3 (1976): 212-239.

into a major subfield of innovation studies and was proclaimed a "new user innovation paradigm" by Dietmar Harhoff and Karim Lakhani in 2016.[19] User innovation studies have investigated the information asymmetry between users and makers ("sticky" information), the various roles users can play in the innovation process (e.g. the crucial role of "lead users"), and they have looked at users' motivation to innovate and share their innovations.[20] More recently, user innovation scholars have shifted their attention to the self-organisation and community-building of innovating users.[21] Ellen van Oost, Stefan Verhaegh and Nelly Oudshoorn, in their study of a wireless network infrastructure, went so far as to replace the term "innovation community" with "community innovation" to emphasise the important role of user collectives at all stages of the innovation process.[22]

This chapter returns to von Hippel's paper of 1976 in the sense that it looks at user innovation in the production of a scientific instrument, the microscope. At the same time, the chapter differs significantly from early approaches to user innovation in two respects. First, the chapter considers the skill and epistemic aspects of making (and innovating) scientific instruments, a dimension that innovation studies scholars – despite their long tradition of case studies centring on the development of scientific instruments – have so far not shown much interest in.[23] Second, the chapter pays more attention to users' community-building and less to the production of prototypes.[24] Whereas von Hippel's study regarded users' production of prototypes as proof of their innovative capacity, the microscopists who corresponded with Abbe only rarely made prototypes themselves.[25] As Marc Ratcliff has shown, the nineteenth century saw a bifurcation of instrument users and makers. Whereas seventeenth- and eighteenth-century microscopists had tended to make their own instruments, in the nineteenth century, most microscopists had their instruments made by microscope manufacturers.[26] Prototypes built

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[19] Dietmar Harhoff and Karim R. Lakhani, "Revolutionizing Innovation: Fundamentals and New Perspectives," in *Revolutionizing Innovation: Users, Communities, and Open Innovation*, ed. Dietmar Harhoff and Karim R. Lakhani (Cambridge, MA: MIT Press, 2016), 2.

[20] For a more comprehensive review of the user innovation studies literature, see Harhoff and Lakhani, "Revolutionizing Innovation."

[21] See, for example, Sonali K. Shah and Cyrus C. M. Mody, "Creating a Context for Entrepreneurship: Examining How Users' Technological and Organizational Innovations Set the Stage for Entrepreneurial Activity," in *Governing Knowledge Commons*, ed. Brett M. Frischmann, Michael J. Madison, and Katherine J. Strandburg (Oxford: Oxford University Press, 2014), 313-339.

[22] See Ellen van Oost, Stefan Verhaegh, and Nelly Oudshoorn, "From Innovation Community to Community Innovation: User-Initiated Innovation in Wireless Leiden," *Science, Technology, & Human Values* 34, no. 2 (2008): 182-205.

[23] For example, von Hippel's 1976 paper reviews cases of user innovation in the production of scientific instruments, but mainly with a view to locating (and quantifying) user innovation for commercial gain, and not to better understand users' skill. See von Hippel, "The Dominant Role of Users in the Scientific Instrument Innovation Process."

[24] Von Hippel himself has turned to studying user innovation communities, for instance in his *Democratizing Innovation* (Cambridge, MA: MIT Press, 2005).

[25] See von Hippel, "The Dominant Role of Users in the Scientific Instrument Innovation Process."

[26] Ratcliff, *The Quest for the Invisible*, 248.

by microscope users in the nineteenth century were mostly ancillary equipment, such as microtomes, dissecting stages or mechanical fingers.[27]

Therefore, British microscopists' contribution to the innovation process at the Zeiss factory mainly consisted of the ideas they shared with Abbe through their letters and periodicals, and whenever they met with him in London. Harhoff has described users' sharing of knowledge with manufacturers as the "periphery" of user innovation.[28] According to him, "core" user innovation revolves around users' prototyping, whereas "peripheral" user innovation provides manufacturers with relevant information derived from use. This chapter, however, seeks to undermine the distinction between the "core" and "periphery" of user innovation and instead acknowledges that using (and tinkering with) technologies, as well as the exchange of innovative ideas, are central features of user innovation and no more "peripheral" than the production of prototypes. Moreover, the chapter enriches innovation studies by offering an alternative account to the Whiggish narratives that continue to underlie much of the management-oriented innovation literature.[29] For example, the chapter recognises the value of commercially unsuccessful innovations in tinkering with and thinking through engineering design.[30]

Von Hippel has argued that "[i]nnovation communities are often stocked with useful tools and infrastructure."[31] In the case of the RMS, these tools and infrastructure allowed Abbe to promote both his theory and, importantly, Zeiss' products, and at the same time learn from British microscopists and test inventions together. By drawing on the innovation studies literature, the chapter provides a fresh perspective on the role of microscopy societies, and natural history societies more generally, in Britain's scientific community in the late nineteenth century. Studying natural historians with a view to innovation allows us to better acknowledge their creative technical solutions to scientific problems. Moreover, a focus on innovation bridges the persistent historiographical divide between the histories of nineteenth-century science and industry. Almost by definition, a history of user innovation in nineteenth-century science firmly embeds commercial technologies in the production of scientific knowledge. Technologies such as Zeiss'

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[27] However, microscopists closely collaborated with microscope manufacturers, not only with Abbe but with various British manufacturers, too. Morrison-Low elaborates on this in her chapters on supply and demand in Morrison-Low, *Making Scientific Instruments in the Industrial Revolution*.

[28] See Dietmar Harhoff, "Context, Capabilities, and Incentives: The Core and the Periphery of User Innovation," in *Revolutionizing Innovation: Users, Communities, and Open Innovation*, ed. Dietmar Harhoff and Karim R. Lakhani (Cambridge, MA: MIT Press, 2016), 27-44.

[29] Benoît Godin's critical review of Ian Fagerberg, Ben R. Martin and Esben Sloth Andersen's (2014) *Innovation Studies: Evolution & Future Challenges* explains some of the problems STS scholars have with management-oriented studies of innovation. Benoît Godin, "'Innovation Studies': Staking the Claim for a New Disciplinary 'Tribe'," *Minerva* 52, no. 4 (2014): 489-495.

[30] Similarly, Franck Cochoy makes a case for introducing a more symmetrical STS approach to business studies in "Driving a Shopping Cart from STS to Business, and the Other Way Round: On the Introduction of Shopping Carts in American Grocery Stores (1936-1959)," *Organization* 16, no. 1 (2009): 31-55.

[31] Von Hippel, *Democratizing Innovation*, 93.

microscopes were not just the result of epistemic discoveries but also a profitable business strategy. Profitability is an important aspect of the production of scientific instruments, which is often neglected in the history of science and technology, but can be analysed using the vocabulary developed in innovation studies.

The rest of the chapter follows the two stages of the controversy surrounding immersion lenses. It first looks at the arguments exchanged between the RMS Fellow Wenham and the American manufacturer Tolles, and how the debate began to reconfigure the knowledge infrastructures of the RMS, before turning to the collaboration between Abbe and the RMS during the later stage of the controversy following Abbe's publication of his theory of microscopic vision.

Making Sense of an Impossible Lens: Ray Diagrams and Calculations

The "battle of the glasses" was fought over immersion lenses, their resolving power and how to measure it. There was consensus among British microscopists that the resolving power of a lens, determining how much detail a user can see in a microscopic image, correlated with its angular aperture. The angular aperture of a lens describes the angle of the cone of light entering the microscope lens from the specimen beneath (*a* in Fig. 4.1). As the angular aperture of a lens increases, so does its resolving power. Hence, front lens *B* in Fig. 4.1 yields a higher resolution than lens *A*. British microscopists also agreed that the medium through which the cone of light passes affects the angular aperture of a lens.

If we imagine the two spaces indicated as working distances (*WD*) in Fig. 4.1 as filled with water instead of air, as is the case with water immersion lenses, the angular aperture *a* of the same lenses would decrease when measured in the denser medium. The theoretical limit of the angular aperture of a dry lens measured in air is 180°, which becomes ca. 97° when the lens is immersed in water and is reduced even further in oil or Canada balsam (ca. 82° in balsam). In the late nineteenth century, most microscopists shared the sense that an angular aperture of 82° in balsam rendered more detail visible than 82° in air, but it was only with Abbe's later introduction of numerical aperture that the effect of the refractive index of the immersion medium was fully considered in measuring aperture. At the beginning of the 1870s, British microscopists were by and large convinced that the angular aperture of an immersion lens could not possibly exceed 82° in balsam, or 97° in water, since a dry lens could not exceed 180° in air.

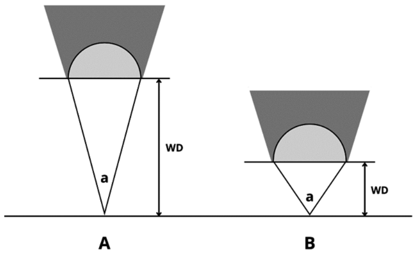

Figure 4.1 Two objectives (A, B) with different angular apertures (a) and working distances (WD).

In 1871, however, the American microscope manufacturer Robert Tolles sent a paper to the *Monthly Microscopical Journal* of the RMS, in which he described an experiment that proved that one of the immersion lenses he had built could achieve an angular aperture of 100° in water.[32] Tolles had learned his trade at the workshop of Charles Spencer, generally considered the first American commercial producer of microscopes.[33] Tolles, together with his agent Charles Stodder, formed the Boston Optical Works in 1867 and became one of the best-known American microscope manufacturers. Tolles' paper of 1871 marked the beginning of the "battle of the glasses" between Tolles and Wenham, which shook British microscopy to its foundations. Looking back at the controversy in 1884, Jacob Cox, president of the American Society of Microscopists, declared that Tolles' lens was "more famous, perhaps, than any other bit of glass ever was."[34]

Tolles' staunchest opponent in Britain was Francis H. Wenham, at the time vice president of the RMS and a marine engineer by training. Born in 1824 as the son of an army surgeon, Wenham had helped to build an Atlantic steamer during his apprenticeship with Great Western Railway in Bristol as a young man. He seems to have been in easy circumstances all his life, being able to take time off to travel the Nile in a self-built river steamer and follow his various interests in marine engineering, photography, aeronautics and microscopy. Wenham had an impressive track record of inventions, including ship engines, a flying machine, a wind tunnel and a binocular microscope. He was well respected among the Fellows and in the beginning his opposition to Tolles found much support. In his annual address of 1870, Joseph Bancroft Reade, then president of the RMS, praised Wenham as "an amateur labourer whose masterly knowledge of the subject and almost unrivalled practical skill fit him to speak *ex cathedrâ*."[35]

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[32] See Robert B. Tolles, "Experiments on Angular Aperture," *The Monthly Microscopical Journal* 6 (1871): 36-38.
[33] See Warner, "'Exploring the Inner Labyrinths of Creation'."
[34] Cox, "Annual Address of the President," 6-7.
[35] Joseph Bancroft Reade, "The President's Address," *The Monthly Microscopical Journal* 3 (1870): 126-127.

The article by Tolles that introduced his seemingly impossible lens to the RMS in 1871 was soon followed by a response by Wenham. The engineer stated that "[a]bout 80° is the utmost aperture that we can expect to obtain for an object mounted in balsam; and the principle does not differ, whether we employ an immersed front or not."[36] Wenham's response was condescending throughout. He implied that Tolles did not understand the most basic optical laws and that he, Wenham, had contrived an experiment to prove these laws but "did not think it worth while to run the risk of injuring [his] object-glasses for demonstrating a simple fact in known optical laws quite incontrovertible."[37] Instead, Wenham reverted to drawing ray diagrams to prove Tolles wrong and his lens a hoax.

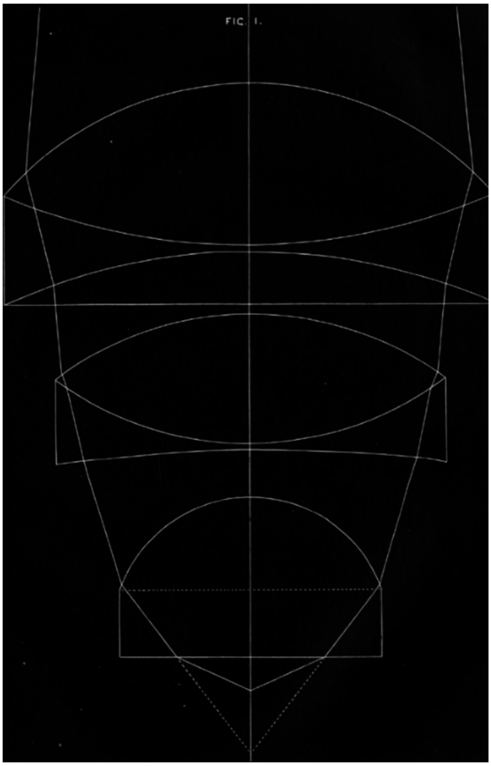

Figure 4.2 Ray diagram made by Francis Wenham to illustrate how rays of light travel through the lenses of an objective. Image from the Biodiversity Heritage Library. Contributed by New York Botanical Garden, LuEsther T. Mertz Library.

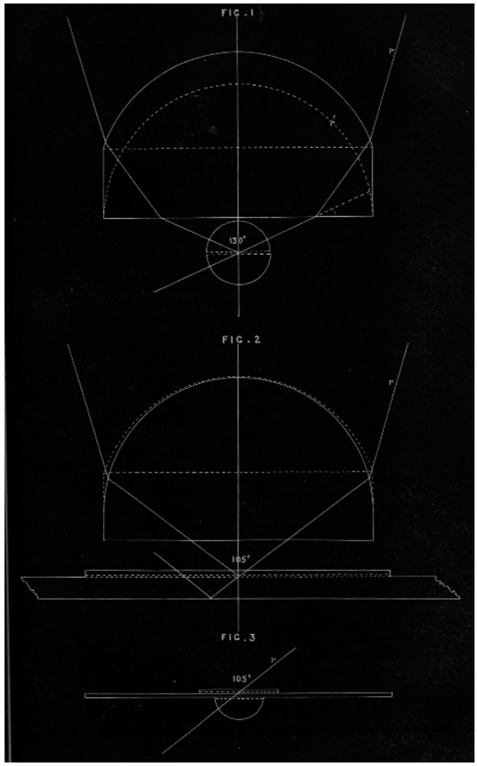

Figure 4.3 Wenham's diagram (Fig. 4.2), adapted by Tolles. Tolles proposed to "borrow in part Mr. Wenham's diagram, for further illustration." Image from the Biodiversity Heritage Library. Contributed by New York Botanical Garden, LuEsther T. Mertz Library.

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[36] Francis H. Wenham, "Mr. Tolles' 'Experiments on Angular Aperture'," *The Monthly Microscopical Journal* 6 (1871): 86.
[37] Wenham, "Mr. Tolles' 'Experiments on Angular Aperture'," 86.

Over the following years, ray diagrams became a central tool for both Wenham and Tolles to promote their ideas. One of the two men would take up a diagram made by the other, adapt it according to his own views and have it reprinted in the journal of the RMS (Fig. 4.2 and 4.3). The ray diagrams thus became what Kathryn Henderson has called "conscription devices," "engineering sketches and drawings … that socially organize the workers, the work process, and the concepts workers manipulate in engineering design."[38] Conscription devices differ from the working images studied in the previous chapters in so far as they are not as closely entangled with observational practices. Whereas working images are a way of probing what is seen with the eye by observing and recording it closely, Wenham and Tolles' ray diagrams were models, intentional abstractions of ray paths through objectives.[39] As Tolles explained himself, in one case he used a diagram made by Wenham although it did not accurately represent Tolles' construction, only to make sure that Wenham had no reason to dispute it.[40]

In line with Henderson's argument, the ray diagrams structured Wenham and Tolles' engineering work while enlisting the support of other microscopists. Moreover, and this is an aspect rather neglected in Henderson's paper, the social organisation that was achieved through these conscription devices at the same time depended on the infrastructure used to disperse them. Whereas the engineers in Henderson's study were co-located at her ethnographic site, an engineering firm, Wenham and Tolles' devices had to cross the ocean between them. To that end, their ray diagrams were printed in the journal of the RMS, which shaped their materiality, reach, and, perhaps most importantly, the temporality of the controversy. The serialisation of the journal directly affected the debate. Sometimes by the time a letter to the editors was printed, another paper or letter, or an extract from another periodical, had been published in the meantime and the discussion had moved somewhere else.[41] The debate further cemented the role of the RMS' periodical as a forum for discussion, and the use of ray diagrams as an argumentative tool.[42] However, as the discussion wore on, the opponents began to think of alternative ways to make their points. Joseph Janvier Woodward, an American

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[38] Kathryn Henderson, "Flexible Sketches and Inflexible Data Bases: Visual Communication, Conscription Devices, and Boundary Objects in Design Engineering," *Science, Technology, & Human Values* 16, no. 4 (1991): 452. See also Wolff-Michael Roth, *Toward an Anthropology of Graphing: Semiotic and Activity-Theoretic Perspectives* (Dordrecht: Kluwer Academic Publishers, 2003); Joeri Bruyninckx, "Sound Science: Recording and Listening in the Biology of Bird Song, 1880-1980" (PhD dissertation, Maastricht University, 2013).
[39] See Nasim, *Observing by Hand*.
[40] See Robert B. Tolles, "On Angular Aperture of Immersion Objectives," *Monthly Microscopical Journal* 8 (1872).
[41] Mussell discusses the temporality of periodicals, and their entanglement with the temporality of physical meetings, in *Science, Time and Space in the Late Nineteenth-Century Periodical Press: Movable Types*. Similarly, Dawson looks at the serialisation of periodicals in *Show Me the Bone*.
[42] Ann La Berge has shown that French periodicals became similar sites of dispute during a debate around the use of microscopy in medicine in the mid-nineteenth century. See La Berge, "Debate as Scientific Practice."

army surgeon and head of the microscopical section at the Army Medical Museum, used one of Tolles' lenses to make photomicrographs that were meant to demonstrate its unprecedented resolving power. Woodward sent his photomicrographs to the RMS. Since they could not be printed in the RMS journal at the time, they were kept in the rooms of the RMS in London and microscopists were invited to come and inspect them.[43] This strengthened the position of the RMS headquarters as a node in the knowledge infrastructures of the debate.

Likewise, the practice of conducting witnessed experiments relied on the premises of the RMS. Tolles decided in 1872 to send one of his immersion lenses to the RMS so the Fellows could test it themselves. Wenham and four other Fellows gathered for a witnessed experiment, which, according to Wenham, would prove once and for all that the angular aperture of Tolles' lens was not as high as the manufacturer claimed. Such witnessed experiments had been a crucial site of knowledge production since the early modern period, and the RMS evidently continued this tradition, with the witnesses testifying to the validity of the experiment in the pages of the society's journal.[44] In the experiment, Wenham first adjusted the lens so that it reached its highest aperture in air and then immersed it.[45] As a result, the lens fell indeed short of the promised aperture. Tolles objected to this practice, explaining that an immersion lens had to be adjusted to the immersion medium, and not to air like a dry lens.[46] However, Wenham refused to change the layout of an experiment that had long been successfully used to measure the aperture of (dry) lenses.[47] In response, Tolles had another experiment conducted in the United States by Woodward, which seemed to refute – but failed to convince – Wenham. As the historian of science Stephen Shapin has repeatedly shown, in the scientific community credibility often relies on personal trust in and familiarity with other practitioners.[48] In the early stages of the aperture debate, the RMS Fellows trusted not only Wenham, but also the setup of an experiment they were familiar with and reluctant to change.

Tolles' next step was to forward the exact measurement of one of his immersion objectives to a mathematician friend of Woodward's, Professor Robert

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[43] See Joseph Janvier Woodward, "Note on the Resolution of *Amphipleura Pellucida* by a Tolles' Immersion 1/5th," *The Monthly Microscopical Journal* 6 (1871): 150-151.
[44] Shapin and Schaffer's classic *Leviathan and the Air-Pump* traces the construction of facts through witnessed experiments in the early modern period. Steven Shapin and Simon Schaffer, *Leviathan and the Air-Pump: Hobbes, Boyle, and the Experimental Life* (Princeton, NJ: Princeton University Press, 1985).
[45] See Francis H. Wenham, "Apertures of Object-Glasses," *The Monthly Microscopical Journal* 9 (1873): 29-32.
[46] See Robert B. Tolles, "An Apparatus for Obtaining the 'Balsam' Angle of Any Objective," *The Monthly Microscopical Journal* 9 (1873): 212-213.
[47] See Francis H. Wenham, "Angular Aperture of Object-Glasses," *The Monthly Microscopical Journal* 11 (1874): 112-119.
[48] See, for example, Steven Shapin, "Cordelia's Love: Credibility and the Social Studies of Science," *Perspectives on Science* 3, no. 3 (1995): 255-275; Steven Shapin, *The Scientific Life: A Moral History of a Late Modern Vocation* (Chicago: University of Chicago Press, 2008).

Keith of Georgetown, DC. Keith undertook "a computation with five figure logarithms," which he considered "much more satisfactory to mathematicians and more easily reviewed than an enlarged drawing."[49] Still, his article was complemented by a variation on a ray diagram that had been made by Wenham and adapted by Tolles. Additionally, Keith provided tables with data obtained by tracing "the course of the rays . . . by the trigonometrical method," a task "not so much more difficult than he [Mr. Wenham] seems to suppose."[50] The latter comment referred to an article by Wenham, in which he had deemed a mathematical approach to measuring the path of light beams through an objective nearly impossible:

> [I]t has been found such a difficult task to calculate the passage of . . . rays . . . through a combination having sixteen surfaces of glass of three different densities and refractions, that even first-class mathematicians have . . . shrunk from the attempt.[51]

John Mayall, a former Secretary of the RMS who came to be one of Abbe's most ardent supporters, submitted Keith's computation "to one of the highest mathematical authorities in England" and found that "the result was against Mr. Wenham."[52] Moreover, by 1874, the London manufacturers Powell & Lealand had seemingly adopted Tolles' measurement and, as was later reported by Jacob Cox, president of the American Society of Microscopists, produced a lens whose "aperture was in excess of the critical 82° in balsam."[53]

Henry Fripp, a Bristol-based microscopist and the first to translate Abbe's work into English, noted in 1876 that Wenham personified "the practical direction to which English microscopists mostly incline" as opposed to the "mathematical exposition of optical laws."[54] Tolles, on the other hand, appeared to have "passed beyond the field of the skillful artisan, into that of a systematic and able investigator, who worked … by the proper application of well understood laws."[55] This assessment of Tolles, made by Cox in 1884, certainly shows some hindsight bias and a scientistic tendency. However, Fripp and Tolles' observations are evidence of a gradual shift in the knowledge infrastructures of the British microscopy community. Starting in the 1870s, ray diagrams were complemented with or replaced by

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[49] See Robert Keith, "Discussion of the Formula of an Immersion Objective of Greater Aperture Than Corresponds to the Maximum Possible for Dry Objectives," *The Monthly Microscopical Journal* 12 (1874): 124-125.
[50] Joseph Janvier Woodward, "Final Remarks on Immersion Apertures," *The Monthly Microscopical Journal* 12 (1874): 126.
[51] Francis H. Wenham, "A New Formula for a Microscope Object-Glass," *The Monthly Microscopical Journal* 9 (1873): 164.
[52] John Mayall, "Mr. J. Mayall, Jun.'s, Critics; and the 'Balsam Aperture Question'," *The Monthly Microscopical Journal* 14 (1875): 215.
[53] Cox, "Annual Address of the President," 35.
[54] Henry Fripp, "On the Limits of the Optical Capacity of the Microscope. By Professor Helmholtz; with a Preface by Dr. H. Fripp," *The Monthly Microscopical Journal* 16 (1876): 18.
[55] Cox, "Annual Address of the President," 6.

calculations and tables, which the RMS journal could accommodate just as well, if not more cheaply. These calculations were entirely different conscription devices. They socially reorganised the work and workers at the RMS by drawing mathematicians like Keith into the pages of the journal, and its community of readers and contributors, while making it more difficult for craftspeople like Wenham to share their ideas. The meetings of the RMS continued to be crucial for practical demonstrations and the sharing of photographs, although the growing camp of Tolles' supporters became somewhat sceptical of Wenham's experimental skills.

It may seem as if the shift towards numerical notation afforded the supremacy of the "systematic and able investigator" over the "skillful artisan," as Cox claimed. The historian of science Ronald Kline has shown that discussions about graphical and numerical notation are indeed tied to the authority of the scientific practitioners who use one or the other, and a more general debate over the value of craft in science.[56] Although the alleged turn away from trial-and-error artisan practices towards numerical methods became a dominant narrative in the microscopy community, even much of Zeiss and Abbe's success still depended on artisanal skill. When Zeiss' only optician who could produce the lenses for high-resolution objectives was drafted into the military service, Zeiss famously failed at finding a replacement and eventually effected the return of the optician to save his business.[57] It is also telling that whereas British microscopists may have thought of Abbe as a theoretician, he was primarily considered an instrument maker among German physicists.[58] It is no surprise, then, that Abbe's work benefitted from the practical skill of the RMS Fellows, as the next section elaborates.

A User Innovation Community: The RMS and Abbe

Applying optical theory and mathematics to the construction of microscopes was considered a challenge not only in Great Britain and the United States but also on the European continent. As the historian Stuart Feffer writes, "[during] the 1840s, '50s and '60s, collaborations between academically trained mathematicians and craft-trained instrument makers became more and more common, but the microscope seemed to remain outside the reach of formal optical theory."[59] At mid-century, physicists still had closer ties to astronomy and the construction of telescopes, with many academics spending part of their career working for (or in close association with) observatories. In comparison to the telescope, the optical principles underlying the microscope had largely failed to attract sustained interest from

[56] For a similar discussion about the value of numerical and graphical methods, see Ronald R. Kline, *Steinmetz: Engineer and Socialist* (Baltimore, MD: Johns Hopkins University Press, 1992). See also the discussion of conscription devices in Bruyninckx, "Sound Science."
[57] See Feffer, "Ernst Abbe," 27.
[58] See Feffer, "Ernst Abbe," 59.
[59] Feffer, "Ernst Abbe," 28.

physicists. Even Ernst Abbe did not show much interest in optics during his studies at Göttingen or his early career as a lecturer at Jena. He initially approached the instrument maker Carl Zeiss, who had set up his workshop for scientific instruments in 1846, to ask him to build an apparatus to measure electrical currents and magnetic fields to accompany his lectures. Zeiss, quite unusual for an instrument maker, had himself attended university lectures on geometry and optics, among other subjects, during his apprenticeship. The two men began collaborating on the production of scientific instruments, which only intensified after Zeiss became Abbe's employer in 1866.

At the Zeiss company, Abbe finally developed a strong interest in the optical principles underlying the microscope. His increasing engagement with microscopy resulted in his theory of microscopic vision, which established the ultimate limit of resolution that could be achieved with a light microscope. In 1872, Abbe submitted his treatise on the theory of image formation in the microscope to Max Schultze's *Archiv für mikroskopische Anatomie*, a journal aimed not so much at theoretical physicists but academic biologists and histologists – potential buyers of Zeiss' instruments.[60] The article, published in 1873, detailed Abbe's understanding of image formation as based on physical, not geometrical, optics, taking into account the wave nature of light. In it, Abbe argued that light diffraction and interference were crucial in creating microscopic images, phenomena that could not be considered in the ray diagrams exchanged by Tolles and Wenham. Abbe's theory challenged the RMS' understanding of microscopy in many ways. Regarding the question of maximum aperture (and resolution), Abbe's theory implied that Tolles was right in assuming that the angular aperture of an immersion lens could exceed 82° in balsam. Abbe also proposed to abolish the concept of angular aperture altogether and replace it with numerical aperture. Instead of measuring the angle of a cone of light, which changed depending on the medium it passed through, Abbe's numerical aperture assigned objectives a numerical value indicating their aperture independent of the immersion medium.

Abbe's paper had been preceded, in 1872, by a series of new objectives by Zeiss, which applied Abbe's theoretical considerations to the production of lenses and were meant to serve as practical proof of their validity.[61] Moreover, Abbe went so far as to devise optical experiments and assembled sets of slides, microscopes and measuring instruments to publicly demonstrate his theory. Stuart Feffer traces Abbe's interest in experimentation back to his studies in Göttingen, where students of the natural sciences, often prospective secondary school teachers, were expected to be able to fashion their own apparatus for in-class demonstrations.[62]

[60] See Feffer, "Ernst Abbe," 44.
[61] See Feffer, "Ernst Abbe," 44.
[62] See Feffer, "Ernst Abbe," 35.

When Abbe went to London for the first time in 1876, he took his experimental apparatus with him and was well equipped to explain his theory at the RMS, considering that many of the Fellows still viewed public experiments as the most reliable proof of theory.

As Abbe's biographer Moritz von Rohr has pointed out, Abbe's visit to the London Loan Exhibition of Scientific Apparatus in 1876 gave him an opportunity to both promote Zeiss' new instruments and gain a better impression of the state of British microscopy.[63] Abbe himself observed that events like the exhibition were not necessary to exchange the kind of information that could be gained from periodicals or through personal correspondence. Yet, the merit of the Loan Exhibition was that it allowed Abbe to "compare that which is usually scattered across space and time."[64] Prior to his journey, Abbe had assumed that further improvement of microscope objectives, in particular with a view to reducing chromatic aberration, hinged on the production of new kinds of glass. The microscopes exhibited – mostly German and British models – seemed to corroborate this assumption, and in his report on the exhibition Abbe stressed the need for research into glass melting.[65] Whereas Abbe, as most continental microscopists, remained sceptical of the large size and finicky accessories of British microscopes, he approved of their fine workmanship, as well as the fact that British and American microscopes used a standardised "society screw" propagated by the RMS.[66] Abbe also wrote fondly of the hospitality extended to him by the microscopists he met, who invited him to examine instruments more closely in private than the exhibition would allow.

During his stay in London, Abbe presented his experiments to corroborate his theory of microscopic vision, but his audience was quite small. Although his 1873 paper had been translated and published by Henry Fripp in the periodical of the Bristol microscopy society, it had failed to attract much attention. Moreover, when Abbe arrived in London for the exhibition in August, the RMS had suspended its meetings due to the annual summer recess, so he could not conduct his experiments at one of the regular RMS meetings. Still, Abbe got to meet at least a few microscopists, most notably John Ware Stephenson, who reached out to the physicist after he had returned to Jena to gain a better understanding of Abbe's experiments. Over the following years, Abbe and Stephenson regularly exchanged their

[63] See von Rohr, *Ernst Abbe*, 98.
[64] "Der Werth derartiger Unternehmungen liegt wesentlich darin, dass sie die Leistungen einer bestimmten Branche auf einen engen Raum concentriren und somit einem vergleichenden Studium des sonst räumlich und zeitlich Getrennten die Wege ebnen." Abbe, "Die optischen Hülfsmittel der Mikroskopie," 122.
[65] Abbe was hoping for – and eventually received – state subsidies to carry out glass melting experiments together with Otto Schott. Since the report was submitted to the German imperial court, it may have seemed like a good opportunity to Abbe to argue his case. See Abbe, "Die optischen Hülfsmittel der Mikroskopie."
[66] Ibid.

ideas, and Stephenson sometimes helped to set up other Fellows' correspondence with Abbe.

Drawing on the innovation studies literature, the postal exchange between Abbe and the Fellows could be described as a, largely virtual, collaboration between a manufacturer and a group of particularly innovative "lead users."[67] The following sections examine this collaboration more closely, looking at how exactly both Abbe and the Fellows profited from their exchanges during the aperture controversy. I show that the British amateurisation of microscopy, here meaning the formation of large-scale knowledge infrastructures mainly by and for researchers without formal scientific training, provided Abbe not only with the means to spread his theory of microscopic vision but also with an opportunity to learn from British microscopists and collaboratively tinker with ideas and instruments. At the same time, Abbe had to adapt to a community with its own rules and moral norms.

Moral Economy

The aperture debate was, as any scientific controversy, bound up with questions of scientific prestige and authority. Whereas Abbe described the battle as a "ridiculous" debate in his report on the Loan Exhibition – which targeted a German audience – he chose his words more carefully in his correspondence with the RMS Fellows and obligingly explained his theory time and time again in his letters and on his subsequent visits to London.[68] Over time, most Fellows came to approve of Abbe's contribution to microscopy, and he was made an Honorary Fellow of the RMS in 1878 – just a few months after Stephenson had given a paper at a society meeting on the homogeneous immersion objectives Abbe had constructed with his help.[69] Francis Wenham never publicly acknowledged his defeat, but by 1881, Abbe's theory, as Stephenson reported, was "accepted by most of our people, although to be candid they cannot in many cases give a reason for the faith that is in them; but it is a great thing to have got them detached from the old heresies."[70] It seems that recognising Abbe's theoretical contribution to the field was a matter of trust as much as understanding.

Gaining scientific authority in British microscopy circles, with some microscopists opposing Abbe's theory initially, was no easy task. The aperture controversy itself was expected to follow certain rules of conduct, which had shaped

[67] Von Hippel coined the term in his 1986 paper, "Lead Users: A Source of Novel Product Concepts," *Management Science* 32, no. 7 (1986): 791–805.
[68] Abbe, "Die optischen Hülfsmittel der Mikroskopie," 147.
[69] See John Ware Stephenson, "On a Large-Angled Immersion Objective, without Adjustment Collar; with Some Observations on 'Numerical Aperture'," *Journal of the Royal Microscopical Society* 1 (1878): 51-56.
[70] Stephenson, John Ware. Letter to Ernst Abbe. 12 Nov. 1881. Nachlass Ernst Abbe, Nr. BACZ 27183.

scientific disputes for centuries.[71] Some of Abbe's closest allies in the RMS were convinced that his manly honour depended on the successful defence of his theory. John Mayall, an acclaimed RMS Fellow and microscope collector, drew on metaphors of chivalry to make his point. He asked Abbe to "don his armour" and give a "'Rowland for an Oliver.'"[72] Wenham, on the other hand, damaged his reputation with his "rough shod energy," making frequent *ad hominem* arguments and "[rushing] in to print head first."[73]

The history of the "battle of the glasses" demonstrates that the British microscopy community was governed by what Robert Kohler and others have termed a "moral economy," moral conventions which "define the mutual expectations and obligations of the various participants" and "regulate access to tools of the trade and the distribution of credit and rewards for achievement."[74] Even after the dust had settled around the aperture question in the 1880s, the correspondence between Abbe and the RMS continued to be shaped by rules of conduct, which were now more implicit than during the controversy. Their exchanges were based on a moral economy that regulated the proper conduct as a member of the RMS and the microscopy community more broadly. Abbe participated in gift exchanges, giving away Zeiss' products to have other microscopists show them to their peers. For example, Romyn Hitchcock, editor of the *American Monthly Microscopical Journal*, offered to act as an agent for Zeiss in the United States without charging any commission. He feared that as soon as he entered business, his journal would be regarded as a trade journal.[75]

Whereas this observation of a moral economy governing scientific exchanges in the nineteenth century is hardly new, it may add an important dimension to the history of innovation. The literature on user innovation communities tends to define these communities as a "commons," a relatively open space where knowledge is exchanged freely.[76] However, the case of Abbe and the RMS shows that although knowledge may be shared without remuneration, knowledge exchange is still shaped by a moral economy, determining fair collaboration, as well as who counts as a member of a community of users, especially in a membership community like the RMS. Robert J. Morris has accurately described nineteenth-

[71] For a more comprehensive study of manners in nineteenth-century scientific debates, see Raf De Bont, "'Writing in Letters of Blood': Manners in Scientific Dispute in Nineteenth-Century Britain and the German Lands," *History of Science* 51, no. 3 (2013): 309-335.
[72] Mayall, John. Letter to Ernst Abbe. 10 Dec. 1880. Nachlass Ernst Abbe, Nr. BACZ 27182 (18).
[73] Mayall, John. Letter to Ernst Abbe. 4 Dec. 1880. Nachlass Ernst Abbe, Nr. BACZ 27182 (16).
[74] Robert E. Kohler, *Lords of the Fly: Drosophila Genetics and the Experimental Life* (Chicago: University of Chicago Press, 1994), 12. See also Chapter Four in Bruyninckx, "Sound Science," and W. Patrick McCray, "Large Telescopes and the Moral Economy of Recent Astronomy," *Social Studies of Science* 30, no. 5 (2000): 685-711.
[75] Hitchcock, Romyn. Letter to Ernst Abbe. 2 Apr. 1880. Nachlass Ernst Abbe, Nr. BACZ 20352 (5).
[76] Shah and Mody refer to user innovation communities as a "particular type of knowledge commons" in "Creating a Context for Entrepreneurship," 315.

century societies as strictly hierarchical "subscriber democracies": society members, who paid high subscription fees to join a society, elected their representatives, usually resulting in a "rule by an oligarchy selected from the higher status members of the society."[77]

The exchange between Abbe and the RMS also demonstrates that the moral economy of the microscopy community was quite compatible with the market economy that Zeiss and other commercial instrument makers moved in. As Joeri Bruyninckx has argued for recordists of birdsong in the twentieth century, business actors latched on to the moral conventions of the birdsong community emphasising that "a successful commercial application of their recordings . . . also represented social capital for recordists."[78] British commercial microscope manufacturers had a long history of collaborating with microscopists, too, often naming instruments after well-known scientists (and microscope users), which increased both the scientist's social capital and the company's monetary gain.[79] Once Abbe had become familiar with the moral conventions of the RMS, he was able to continue those longstanding collaborations between microscope users and makers. As the following section shows, the moral economy of the RMS also served Abbe well in the sense that the trusting relationship he and the Fellows developed protected their ideas from being exploited by outsiders.

Alternatives to Patenting

The microscopists involved in the aperture debate were attracted to Abbe's theory of microscopic vision because it provided theoretical proof of Tolles' claims regarding the aperture and resolution of his immersion lens, and because it answered the question of what the limit of resolution was that could be achieved with a light microscope, at least in theory. Abbe himself, however, was more interested in how his calculations could help him overcome optical aberrations in Zeiss' objectives. Unlike many of the RMS Fellows, Abbe believed that the quality of an objective should not primarily be judged by its resolving power but by the overall clarity of the image it produced, which should be free from aberrations. This was in line with the work practices of Zeiss' German academic customers, who were overall more interested in obtaining clear microscopic images with a long depth of field than outcompeting each other in resolving the most minuscule objects.[80] Abbe suspected that further improvements in Zeiss' objectives could only be

[77] Robert J. Morris, "Voluntary Societies and British Urban Elites, 1780-1850: An Analysis," *The Historical Journal* 26, no. 1 (1983): 101.
[78] Bruyninckx, "Sound Science," 104.
[79] See Joshua Nall and Liba Taub, "Selling by the Book: British Scientific Trade Literature after 1800," in *How Scientific Instruments Have Changed Hands*, ed. Alison D. Morrison-Low, Sara J. Schechner, and Paolo Brenni (Leiden: Brill, 2016), 21-42.
[80] See Feffer, "Ernst Abbe."

achieved with new kinds of optical glass. In 1876, Abbe decided to visit the Loan Exhibition of Scientific Apparatus in London in order to compare a wide range of microscopes and confirm his idea.

His report on the British Loan Exhibition included a plea for more research into glass melting, which foreshadowed his attempts to receive state subsidies to produce new kinds of glass that would reduce the chromatic aberration in Zeiss' objectives. In 1881, Abbe, together with the chemist Otto Schott, began to research the optical qualities of different glasses and how they were affected by the materials used in the melting process. The two men soon realised that, whereas the melting of small batches of glass for their research was affordable, scaling up their production of glass required more capital than they had at their disposal. To them, state subsidies seemed the most promising route to acquire additional funds. He and Schott argued that their goal was to produce any kind of glass that scientists – be they microscopists, chemists or astronomers – could possibly desire, even though producing the more extraordinary kinds of glass would probably not be economically viable.[81] Eventually, in 1884, Abbe and Schott managed to convince the Prussian ministry officials of their plan and received funding for their research and glass production.[82]

Emphasising the scientific value of their work, and their disinterestedness in financial profit, was the main argument Abbe and Schott made to acquire state funding. In an 1882 progress report submitted to Wilhelm Foerster, an influential astronomer with strong ties to German state officials, Abbe and Schott vowed not to patent any of their research results but to make them publicly accessible.[83] Abbe had long been opposed to patenting. It was only in the 1890s that he started to patent a few of Zeiss' instruments, mostly measurement devices. As he saw it, "the most valuable patents [were] those which we [the Zeiss company] did not take out and did not need to take out."[84] Abbe trusted that the superior workmanship of Zeiss' products would speak for itself, attracting enough customers even if competitors offered similar, but inferior, products. Even when Henry Crouch, a London microscope maker, directly inquired about the formulas used at Zeiss to make objectives, Abbe appears to have been at ease to share them.[85]

[81] Abbe and Schott, "Vorläufiger Bericht," 22.
[82] Moritz von Rohr, "Vorwort," in *Gesammelte Abhandlungen von Ernst Abbe*, ed. Moritz von Rohr, vol. 4 (Hildesheim: Georg Olms, 1989), VIII.
[83] Abbe and Schott, "Vorläufiger Bericht," 26.
[84] "…die…wertvollsten Patente [waren] diejenigen …, welche wir überhaupt nicht genommen haben und nicht zu nehmen brauchten." Ernst Abbe, "Über die Grundlagen der Lohnregelung in der Optischen Werkstätte," in *Gesammelte Abhandlungen von Ernst Abbe*, ed. Moritz von Rohr (Hildesheim: Georg Olms, 1989), 135.
[85] In 1874, Crouch sent Abbe a letter asking him to share his calculations if possible and thanked him for his kind reply a few months later. Crouch, Henry. Letter to Carl Zeiss. 8 Dec. 1874. Nachlass Ernst Abbe, Nr. BACZ 20342; Crouch, Henry. Letter to Ernst Abbe. 2 Mar. 1875. Nachlass Ernst Abbe, Nr. BACZ 20342 (2).

In their study of patenting in the English brewing industry in the long eighteenth century, Alessandro Nuvolari and James Sumner have looked at alternatives to patenting, which they term "alternative appropriability strategies."[86] Until the early nineteenth century, these strategies largely consisted of various degrees of secrecy and openness. While secrecy may seem like the obvious choice to protect technological innovations, openness was harmless as long as no competitor was able to reproduce the innovation, and it had the added benefit of increasing the prestige of the inventor. Revealing only some information that proved the expertise of the inventor but was not enough to build a technology was a way of combining the benefits of both secrecy and openness. Moreover, as Nuvolari and Sumner show, a "careful selective revealing of information, and a sophisticated approach to the communication of inventions, could allow a 'trade in inventions' to thrive."[87] It could be argued that Abbe and Schott's openness was harmless since it was indeed difficult for others to compete with their work. Establishing Schott's glassworks in Jena enabled Zeiss to vertically integrate glassmaking in the workshop's production of instruments, and the new kinds of glass devised by Abbe and Schott gave the company a first mover advantage. The instrument maker Carl Bamberg, who strongly supported the research into glassmaking in Jena, testified to Foerster in 1883 that the main foreign competitors in glassmaking – Chance in Birmingham and Feil in Paris – were a long shot from delivering the fine quality of glass that Schott produced.[88]

The correspondence between Abbe and the RMS suggests that Abbe's personal attachment to the British microscopy community may have been an additional appropriability strategy. Sonali Shah and Cyrus Mody have, in their research into user innovation, suggested that (user) entrepreneurs benefit from being emotionally involved in user innovation communities. In addition to the emotional reward, these entrepreneurs tend to have better access to their peers' ideas, since users are more likely to share them with insiders than outsiders.[89] In the case of Abbe and his RMS correspondents, their companionship and mutual trust, much like a patent, protected their innovations to outsiders. John Mayall, for instance, contrived a way of using a part of Abbe's apertometer – a device for measuring aperture – as an illuminator. In one of his letters to Abbe he wrote: "I could get my suggestions carried out here [in London] at once, but I don't think it would be fair to allow any other optician than Mr. Zeiss to work at it."[90] Stephenson, on the other hand, kept Abbe informed about the progress his competitors in London made.

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[86] Alessandro Nuvolari and James Sumner, "Inventors, Patents, and Inventive Activities in the English Brewing Industry, 1634–1850," *Business History Review* 87, no. 1 (2013): 98.
[87] Ibid., 119.
[88] Carl Bamberg, "C. Bamberg's 'Brandbrief' vom 7.X.83," in *Gesammelte Abhandlungen von Ernst Abbe*, ed. Moritz von Rohr (Hildesheim: Georg Olms, 1989), 32-35.
[89] Shah and Mody, "Creating a Context for Entrepreneurship," 331.
[90] Mayall, John. Letter to Ernst Abbe. 9 Sep. 1878. Nachlass Ernst Abbe, Nr. BACZ 27182 (2).

For example, he assured Abbe that even in 1881, Powell & Lealand, one of the leading firms at the time, did “not know anything about the refractive indeces” and did “not know the relation between densities & indeces.”[91] Stephenson’s reports thus enabled Abbe to better assess the entrepreneurial risk of his openness. Abbe, in turn, made sure to credit the Fellows for their inventions. In order to establish with certainty who should be credited with an invention, Abbe turned to the RMS’ collections of instruments.

Consulting Collections

The Loan Exhibition of 1876 explicitly invited its participants to exhibit historical scientific instruments.[92] As a result, a large collection of historical instruments was displayed, which made a lasting impression on Abbe. Notably, he mentioned a one-meter microscope by the French manufacturer Nachet in his report, which proved that an outsized tube did not improve the optical qualities of a microscope.[93] This instrument and other rarities at the exhibition were part of private collections of instruments, which Abbe considered “an example of the enthusiasm and liberal approach English citizens take to scientific issues.”[94] Sam Alberti, in an article on nineteenth-century natural history collections and their owners, confirms Abbe’s contemporary observation that English private collectors amassed a wealth of scientific objects in the nineteenth century.[95] These personal collections, some of them building on eighteenth-century cabinets, were complemented by society collections in the first half of the nineteenth century. After all, collecting scientific specimens was one of the main objectives of nineteenth-century natural history societies. The resulting collections were exhibited, and over the past few decades historians of science have increasingly recognised the importance of collecting as a scientific practice in the nineteenth century.[96]

The comprehensive RMS collection of books, slides and instruments largely depended on the contributions of private collectors like John Mayall and

[91] Stephenson, John Ware. Letter to Ernst Abbe. 24 Sep. 1881. Nachlass Ernst Abbe, Nr. BACZ 27183.
[92] See Ernst Gerland, "Bericht über den historischen Theil der internationalen Ausstellung wissenschaftlicher Apparate in London im Jahre 1876," in *Bericht über die wissenschaftlichen Apparate auf der Londoner internationalen Ausstellung im Jahre 1876*, ed. August Wilhelm von Hofmann (Braunschweig: Friedrich Vieweg und Sohn, 1878), 1.
[93] Abbe, "Die optischen Hülfsmittel der Mikroskopie," 126.
[94] Abbe, "Die optischen Hülfsmittel der Mikroskopie," 125.
[95] See Samuel J. M. M. Alberti, "Placing Nature: Natural History Collections and Their Owners in Nineteenth-Century Provincial England," *The British Journal for the History of Science* 35, no. 3 (2002): 291-311.
[96] There is a wealth of literature dealing with collecting as a nineteenth-century scientific practice in Britain, among the best-known works are Anne Secord, "Science in the Pub: Artisan Botanists in Early Nineteenth-Century Lancashire," *History of Science* 32, no. 97 (1994): 269-315; Jim Endersby, "’From Having No Herbarium’: Local Knowledge Versus Metropolitan Expertise: Joseph Hooker's Australasian Correspondence with William Colenso and Ronald Gunn," *Pacific Science* 55, no. 4 (2001): 343-358; Secord, "Pressed into Service."

Frank Crisp, a London lawyer who supported Abbe in the aperture debate and who is estimated to have owned nearly 3,000 microscopes.[97] At the height of the British amateurisation of science in the 1860s and 1870s, the RMS collection grew considerably, benefitting from donations made by an increasing number of RMS Fellows. In 1868, the RMS already owned 11 microscopes, 1,114 slides, and 240 books.[98] Over the following decades, the collection grew further, consisting of 46 microscopes and ca. 4,000 slides in 1898.[99] While historians of science and technology tend to focus on either the collection or exhibition of scientific instruments, Alberti has stressed the need to "bridge the critical gap between the processes of collection and exhibition and begin to construct a more rounded cultural study of natural history collections."[100] Or, as the historian of science and scientific instruments Liba Taub asks: "Once in collections, how were they [scientific instruments] used?"[101] Abbe used the RMS collection, and the personal collections of the Fellows, as an inventory of past inventions. This way of using collections of scientific instruments seems to have received little attention in the innovation studies literature, as well as among historians of science and technology.

As Abbe saw it, collections gave him the rare opportunity to directly compare the construction and optical qualities of instruments and learn from them.[102] Abbe consulted the RMS collection and the private collections of the Fellows on his visits to London, and he regularly wrote to the Fellows to obtain information about historical inventions. Moreover, he was careful not to claim ideas as his that others had had before. In the case of homogeneous immersion, Abbe researched immersion lenses of the past, together with his RMS correspondents, to make sure that the idea underlying the lenses made by Zeiss indeed originated from his correspondence with Stephenson.[103] Thus, collections not only informed the work of nineteenth-century scientists, as historians of science have long shown, but some of them were also a trove of past inventions that manufacturers like Zeiss could draw on. This may be a useful insight for innovation studies scholars since there is reason to believe that microscopists are not the only group of dedicated users of a

[97] Gerard L'E. Turner, "'Some Curious Old Instruments': The Assembly of the Royal Microscopical Society's Collection of Microscopes," *Journal of the History of Collections* 1, no. 2 (1989): 158.
[98] For the number of microscopes, see Turner, "'Some Curious Old Instruments'," 152. The number of books and slides is mentioned in James Glaisher, "The President's Address for the Years 1867-1868," *Transactions of the Royal Microscopical Society* 16, new series (1868): 61-85.
[99] For the number of microscopes, see Turner, "'Some Curious Old Instruments'," 152. The number of slides is mentioned in "Proceedings of the Society," *Journal of the Royal Microscopical Society* (1897): 595.
[100] Alberti, "Placing Nature," 293.
[101] Liba Taub, "What Is a Scientific Instrument, Now?," *Journal of the History of Collections* 31, no. 3 (2019): 453.
[102] See Abbe, "Die optischen Hülfsmittel der Mikroskopie."
[103] See Abbe, "Ueber Stephenson's System der Homogenen Immersion bei Mikroskop-Objektiven."

technology who form collections.[104] Collections, despite their air of conservation rather than innovation, may be crucial in the innovation process, asking scholars of user innovation to pay them more attention in their research.

The Scientific Ideals of the RMS

While Abbe became engrossed in researching and producing different kinds of optical glass to reduce aberration effects, many of the RMS Fellows continued to be more invested in using his theoretical insights to approach the ultimate limit of microscopic vision. As set forth in the charter and bylaws of the RMS, the society had been established for "the promotion and diffusion of improvements" in the construction and application of the microscope; for the discussion of such improvements and microscopical observations; for the establishment of exhibitions and collections; for "submitting difficult and obscure microscopical phenomena to the test of instruments of different powers and constructions;" and for the establishment of a library.[105] Additional initiatives carried out over the following decades included the standardisation of instruments and units of measure, the construction of a sturdy museum microscope that could withstand being handled by museum visitors, and advocating for the use of microscopes in school education. The RMS often achieved its goals by organising competitions, such as inviting microscope manufacturers to compete for the best affordable microscope they could make, which helped to reduce the prices for microscopes. The RMS' competitive spirit also marked the Fellows' attempts at resolving ever-smaller objects, which was spurred by the "battle of the glasses" and became an end in itself for some Fellows.

Von Rohr has argued that Abbe was hard-pressed to find a similarly dedicated and institutionalised community of microscopists in the German Empire.[106] Zeiss' customer base grew steadily, and the company's microscopes were gaining a reputation with German scientists, but there was considerably less interest in discussing the construction of microscopes from a theoretical perspective. Some organisations, most notably the Deutsche Gesellschaft für Mechanik und Optik, did represent instrument makers and furthered discussion about the production of scientific instruments, but they tended to be concerned with economic issues like

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[104] For instance, Füller, Jawecki and Mühlbacher mention collections of basketball shoes as a distinctive feature of user innovators in online basketball communities, but they do not look at what user innovators *do* with their collections. Johann Füller, Gregor Jawecki, and Hans Mühlbacher, "Innovation Creation by Online Basketball Communities," *Journal of Business Research* 60, no. 1 (2007): 60-71.
[105] See Frank Crisp's 1878 summary of the objectives of the society, "On the Present Condition of Microscopy in England," *Journal of the Royal Microscopical Society* 1 (1878): 121.
[106] See von Rohr, *Ernst Abbe*.

tariffs and other trade barriers.[107] For a while, Abbe found an intellectual sparring partner in Leopold Dippel, professor of botany at Darmstadt, who contacted the physicist to include his theory of microscopic vision in a new edition of Dippel's *Das Mikroskop und seine Anwendung*.[108] Overall, however, it seems safe to say that the RMS was more interested in understanding and promoting Abbe's work than any German organisation.

Sometimes, the Fellows seemed to take even more interest in the optical principles of microscopy than the physicist himself. When Abbe finally replied to Stephenson's letters concerning the construction of homogeneous immersion lenses, he wrote that he had only considered homogeneous immersion from the perspective of possible applications. As he saw it, homogeneous immersion required an immersion fluid of high refractive index (likely oil) that was disadvantageous to most of the research undertaken with microscopes. Abbe mainly saw the benefit of homogeneous immersion in alleviating the spherical aberration in a microscope and making cover glass correction collars superfluous.[109] He imagined that petrography might profit from homogeneous immersion, but this did not seem to warrant the effort and cost of producing homogeneous immersion lenses.[110]

Like Abbe, Stephenson argued that homogeneous immersion would help overcome coverslip correction and make microscope objectives easier to handle. Stephenson wrote to Abbe in August 1877 that he considered this "a great advantage as … many fine objectives are condemned because their owners are unable to use them properly."[111] In the postscript of a letter sent in December the same year, Stephenson briefly added that "the limit of vision as far as resolution of lines under immersion glasses is concerned will be extended by your new objective."[112] Extending the limit of vision was hard to justify from a purely utilitarian perspective, since there did not seem to be many practical reasons to do so, but Stephenson considered it an interesting scientific challenge. Stephenson, in accordance with the objectives of the RMS, had a keen interest in the optical principles underlying the construction of microscopes. He admitted to Abbe that in microscopy, he "[took] more interest in the objectives than in the objects themselves."[113] More than once, Stephenson asked Abbe to consider the construction of instruments that "would not be worth the trouble … from a commercial point of view, but from

[107] For a more detailed account of the role of the Deutsche Gesellschaft für Mechanik und Optik in the making of high-precision mechanics, see Jörg Zaun, *Instrumente für die Wissenschaft: Innovationen in der Berliner Feinmechanik und Optik 1871-1914* (Berlin: BibSpider, 2002), 197.
[108] See Feffer, "Ernst Abbe."
[109] See Abbe, "Ueber Stephenson's System." Cover glass correction collars help to adjust a microscope objective to coverslips of varying thickness.
[110] See Abbe, "Ueber Stephenson's System."
[111] Stephenson, John Ware. Letter to Ernst Abbe. 2 Aug. 1877. Nachlass Ernst Abbe, Nr. BACZ 27183.
[112] Stephenson, John Ware. Letter to Ernst Abbe. 1 Dec. 1877. Nachlass Ernst Abbe, Nr. BACZ 27183.
[113] Stephenson, John Ware. Letter to Ernst Abbe. 10 Feb. 1879. Nachlass Ernst Abbe, Nr. BACZ 27183.

a scientific standpoint … would certainly be of very great interest."[114] Apparently, this thought stuck with Abbe, as he later explained that Stephenson's argument changed his perspective on homogeneous immersion by framing it as a means of approaching the limit of microscopic vision and, thus, a matter of more general scientific interest.[115]

The interest the RMS Fellows took in the construction of microscopes complicates von Hippel's original definition of users profiting from the *use*, not the sale, of a technology, which used to be a mainstay in the innovation studies literature.[116] Stephenson at least was not much concerned with the study of microscopic objects or using Zeiss' instruments for research. Rather, reaching the limit of microscopic vision was an intriguing puzzle and an end in itself. Recently, innovation studies scholars have come to acknowledge users' more intrinsic motivation to tinker with technologies.[117] Often, the tinkering – and, in Stephenson's case, the theoretical insights gained from it – is reward enough, or at least complements more utilitarian motives. The correspondence between Abbe and Stephenson raises the question if manufacturers who do not consider financial gain their utmost priority may be more susceptible to users' non-utilitarian inventions. Given that Abbe had a scientific background himself, and considering that he and Schott emphasised their non-commercial interests to receive state subsidies, Stephenson's argument fell on fertile ground.

Infrastructural Allies

Stephenson and a few other RMS Fellows who supported Abbe's work not only provided Abbe with innovative ideas regarding the construction of scientific instruments, but also taught him how to use the RMS' knowledge infrastructures. They translated and published Abbe's papers in their society journal, asked him to make wallcharts that could be exhibited in London, and the RMS Fellow John Mayall encouraged Abbe to argue his case in the *English Mechanic*, a magazine that made up what it lacked in reputation with its wide circulation.[118] The Fellows,

[114] Stephenson, John Ware. Letter to Ernst Abbe. 2 May 1878. Nachlass Ernst Abbe, Nr. BACZ 27183.
[115] See Abbe, "Ueber Stephenson's System."
[116] In his early work, von Hippel defined users as those who profit from the use of technologies, as opposed to the manufacturers, who profit from selling them. However, von Hippel has come to acknowledge the more intrinsic motivations of innovating users, see the following footnote.
[117] See, for example, Ruth Maria Stock, Pedro Oliveira, and Eric von Hippel, "Impacts of Hedonic and Utilitarian User Motives on the Innovativeness of User-Developed Solutions," *Journal of Product Innovation Management* 32, no. 3 (2015): 389-403; Christina Raasch and Eric von Hippel, "Innovation Process Benefits: The Journey as Reward," *Sloan Management Review* 55, no. 1 (2013): 33–39; Karim R. Lakhani and Robert G. Wolf, "Why Hackers Do What They Do: Understanding Motivation and Effort in Free/Open Source Software Projects," in *Perspectives on Free and Open Source Software*, ed. Joseph Feller et al. (Cambridge, MA: MIT Press, 2005), 3–21.
[118] Mayall, John. Letter to Ernst Abbe 3 Feb. 1881. Nachlass Ernst Abbe, Nr. BACZ 27182 (19); Mayall, John. Letter to Ernst Abbe. 29 Nov. 1880. Nachlass Ernst Abbe, Nr. BACZ 27182 (14).

therefore, became "infrastructural allies," in Anne Beaulieu's sense of the term, actors who "modulate access to sites of knowledge production" and who helped Abbe gain access to the RMS' knowledge infrastructures.[119] To communicate his theory of microscopic vision and learn from the Fellows, it was crucial for Abbe to understand the communication mechanisms at work in the RMS.

Shah and Mody have observed that user innovation communities tend to establish "one-to-many communication mechanisms" that entrepreneurs can tap into.[120] The most prominent one-to-many mode of communication of the RMS was probably its periodical, which started as the *Transactions of the Microscopical Society of London* in 1844.[121] By the time Abbe arrived in London, the periodical had undergone several changes of editors, as well as entire overhauls. Its title had changed to *The Monthly Microscopical Journal: Transactions of the Royal Microscopical Society, and Record of Histological Research at Home and Abroad*, edited by Henry Lawson, assistant physician and lecturer of physiology at London's St. Mary Hospital. The journal's title reflected its change in content, as it aspired to circulate information about not only British but also foreign microscopical findings, and to appeal to professional histologists.[122]

The journal made scientific papers, abstracts, reviews and correspondence available to its readers. During the aperture debate, letters sent to the editor, often directly addressing letters sent by Tolles, Wenham and others involved in the debate, seem to have been the most frequently used one-to-many communication mechanism. However, a closer look at the correspondence between Abbe and the RMS Fellows reveals that even letters to the editor signed by one correspondent were often the result of collaborative attempts at countering the arguments made by the adverse party. In their private correspondence, the Fellows and Abbe deliberated on appropriate replies and formulated them together, making their letters to the journal a few-to-many, rather than one-to-many, mode of communication. All the while, the personal letters Abbe sent to the Fellows would be circulated among his allies in the RMS, turning one-to-one personal correspondence into a one-to-few mode of communication. The debate required the Fellows to take sides, with the different camps coming together through collaborative writing.

Abbe had to communicate his findings in English and sometimes needed the Fellows' help to do so, even though Abbe's English correspondents were in awe of his command of their language. Stephenson told Abbe in 1881, "[how] you can have done so much in English is to me wonderful. I suggested to Crisp that he

[119] Anne Beaulieu, "From Co-Location to Co-Presence: Shifts in the Use of Ethnography for the Study of Knowledge," *Social Studies of Science* 40, no. 3 (2010): 461.
[120] Shah and Mody, "Creating a Context for Entrepreneurship," 331.
[121] Between 1839 and 1844, the society's transactions were not published by the RMS but appeared in other periodicals. For a more detailed account of the pre-history of the RMS' periodical, see Brock, "Patronage and Publishing."
[122] Brock writes that the RMS Fellows wanted the journal to "distance itself from the tradition of 'amateur' natural history" in "Patronage and Publishing," 253.

should return the compliment by sending you an article of equal length & quality in German."[123] Frank Crisp had translated Abbe's theory and presented it as a paper at a meeting of the London Quekett Microscopical Club in 1878. The first English translation of Abbe's work, undertaken by Henry Fripp and published in the periodical of the Bristol natural history society, had contained some inconsistencies and largely failed to convince British microscopists of the value of Abbe's theory.[124] The correspondence Abbe took up with the Fellows in the late 1870s helped to improve the translations of his work. Often, Abbe would roughly translate his texts, send them to the Fellows to polish his English, who would then send the texts back to the physicist to see if he still agreed with their choice of words. Despite these painstaking translations of Abbe's work, there were still material constraints that affected their publication in the RMS journal and other periodicals. Fripp lamented that some microscopists knew of Abbe's theory only from "some 'extracts' jumbled together in disconnected form … I [Fripp] complained of this to the editor Dr. Lawson last year but his answer was that he could not print the essay in full and his co-editors prepared 'extracts'."[125] Thus, the journal's practice of providing readers with an overview of the microscopical work done abroad sometimes worked to the disadvantage of comprehensive foreign papers, which would not be printed in full.

Abbe's allies in the RMS sought to compensate the shortcomings of their journal by demonstrating his work through witnessed experiments. As argued in the section on microscopists' moral economy, practical demonstrations remained exceedingly popular with microscopists on the British Isles – so much so that Abbe's correspondents reproduced his experiments, sometimes asking him for guidance in their letters. John Mayall, one of the RMS Fellows, reminded Abbe of the importance of witnessed experiments and the need to refute them in one of his letters:

> Bear in mind we know the effect on the English mind of a distinct and final refutation of an alleged practical demonstration … So please put on your thinking cap – take pen in hand and compasses – and let that "practical demonstration" be rooted out to the very foundation …[126]

[123] Stephenson, John Ware. Letter to Ernst Abbe. 9 Mar. 1881. Nachlass Ernst Abbe, Nr. BACZ 27183.
[124] Barry Masters puts the lack of support for Abbe's theory down to Fripp's poor translation. Barry R. Masters, *Superresolution Optical Microscopy: The Quest for Enhanced Resolution and Contrast* (Cham: Springer Nature Switzerland, 2020).
[125] Fripp, Henry. Letter to Ernst Abbe. 23 Dec. 1876. Nachlass Ernst Abbe, Nr. BACZ 20369 (4).
[126] Mayall, John. Letter to Ernst Abbe. 20 Mar. 1881. Nachlass Ernst Abbe, Nr. BACZ 27182 (23).

Frank Crisp conducted Abbe's experiments at a meeting of the Quekett Microscopical Club, while Romyn Hitchcock exported them to New York.[127] These experiments continued the long tradition of hosting practical demonstrations at the meetings of learned societies, and reproducing them elsewhere. While reports of witnessed demonstrations printed in periodicals helped to gather virtual witnesses, Abbe and his correspondents continued to rely on physical replications to further the acceptance of his theory.[128]

Crucially, these practical demonstrations came to be part of the innovation process. Although meant to merely replicate Abbe's theory of image formation in microscopes, and prove the benefits of immersion lenses, the experiments conducted at society meetings opened possibilities for experimenters to tinker with the technologies used in them and use them differently than intended. At an RMS meeting in 1878, John Mayall conducted an experiment to show that an immersion lens could have an aperture exceeding the maximum aperture of a dry lens. He used Abbe's measuring device, an apertometer, to do so and in the process realised that one part of the apertometer might well be used for illumination. Mayall asked Abbe to adapt the apertometer in such a way that it could be turned into an illuminating apparatus, and Abbe had a prototype produced by Zeiss.[129] It is unclear if the apertometer-turned-illuminator ever moved beyond the prototype stage – it does not seem to appear in the company's trade catalogues – but it is a striking example of how having Abbe's experiments replicated abroad fuelled the creative use of the instruments produced by Zeiss.

The infrastructures used by Abbe and his correspondents each offered different possibilities for exchanging ideas about Abbe's theory and ways of using Zeiss' instruments, as well as various constraints. Reports published in the periodical of the RMS gathered virtual witnesses, but the periodical's practice of "jumbling together" extracts of Abbe's work jeopardised the acceptance of this theory. The comparatively limited reach of personal letters could be enhanced by circulating and publishing them. During the aperture debate, letters became collaborative, argumentative tools that gathered the two opposing camps around them. Experiments, finally, although mainly meant to support Abbe's theory, became sites for tinkering and thinking along with technologies. This shows that whereas Abbe became known for his thorough theoretical understanding of microscopy among British microscopists, craft remained central to his innovations – at Zeiss' workshop but also in replicating Abbe's experiments abroad and devising creative new ways of using his optical instruments.

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[127] Masters mentions Crisp's experiments in *Superresolution Optical Microscopy: The Quest for Enhanced Resolution and Contrast*. Romyn Hitchcock writes about his plan to conduct Abbe's experiments in New York in a letter to Abbe, 10 Jan. 1879. Nachlass Ernst Abbe, Nr. BACZ 20352 (1).
[128] Steven Shapin and Simon Schaffer's classic *Leviathan and the Air-pump: Hobbes, Boyle, and the Experimental Life* studies the origin of this fact-making process in the early modern age in depth.
[129] Mayall, John. Letter to Ernst Abbe. 9 Sep. 1878. Nachlass Ernst Abbe, Nr. BACZ 27182 (2).

In 1881, Stephenson regarded the aperture question as settled.[130] Francis Wenham never conceded defeat and went on to publish his work in the *English Mechanic,* but the editors of the RMS journal refused to continue printing his polemical pieces. By then, the debate had affected the RMS, its members and knowledge infrastructures, in many ways. Wenham's authority was irreparably damaged, geometrical optics and their representation through ray diagrams in the society's journal had begun to give way to the numerical notations of physical optics, and some of Abbe's supporters had become estranged from the society. Crisp, in the infamous speech he gave on the state of English microscopy in 1878, lamented that "there is probably no body of men who devote so little real attention to the principles that lie at the root of that branch of science of which they are disciples, as do the English microscopists."[131] Four years later, Stephenson admitted to Abbe that he had withdrawn from the Council of the RMS, explaining that although "there are many members for whom [he has] the greatest respect, this does not quite apply to all."[132]

Innovation studies scholars have termed such tensions among innovating users "creative abrasion," a clash of different experiences, kinds of expertise and approaches to problem solving that is part of the creative process.[133] But the concept of creative abrasion does not quite capture the enormous impact of controversies in reconfiguring a user innovation community, such as the deep changes the British microscopy community underwent and their lasting effect on the construction of microscopes. By the time Ernst Abbe arrived in London in 1876, ways of sharing knowledge within the RMS had diversified. Journals with their diagrams, calculations, reprinted paper extracts and correspondence columns existed alongside photomicrographs, private correspondence networks, as well as RMS meetings and practical demonstrations. The "battle of the glasses" between Tolles and Wenham had spurred this development, since it had asked microscopists on both sides of the Atlantic to devise ever new ways of convincing their opponents – or to reify old traditions like the witnessed experiment.

Harking back to the first chapter and Janet Vertesi's work on seamful spaces, we can conceive of these multiple, co-existing ways of sharing knowledge as distinct but overlapping infrastructures, asking us to look at "how actors work locally and creatively to reconcile [them]."[134] Using these infrastructures required

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[130] Stephenson, John Ware. Letter to Ernst Abbe. 12 Nov. 1881. Nachlass Ernst Abbe, Nr. BACZ 27183.
[131] Crisp, "On the Present Condition of Microscopy in England," 121.
[132] Stephenson, John Ware. Letter to Ernst Abbe. 18 Jan. 1882. Nachlass Ernst Abbe, Nr. BACZ 27183.
[133] See Leonard-Barton and Swap, *When Sparks Fly: Igniting Creativity in Groups*.
[134] Vertesi, "Seamful Spaces," 270.

some “heterogeneous engineering,” producing “fleeting alignment or misalignment of infrastructures to accomplish local, mundane tasks.”[135] In accordance with Vertesi’s concept of seamful spaces, Abbe’s membership in the microscopy community, and his ability to draw on other members’ innovations, depended on his skilful engineering of the RMS’ knowledge infrastructures. The heterogeneous engineering of Abbe and his allies was not so much local but far-reaching and sometimes virtual, aligning instruments, experiments, correspondence and publications to communicate over great distances.[136]

The effect of the aperture debate on Abbe’s heterogeneous engineering was twofold. First, the controversy between Tolles and Wenham exposed and diversified the RMS’ infrastructures, offering Abbe more possibilities of promoting his theory and thinking, or tinkering, along with the RMS Fellows. Second, the debate spurred Abbe’s supporters to help him navigate these infrastructures by suggesting when to respond to a polemic in which publication, or when to resort to a practical demonstration to make his case. This shows that controversies may expose infrastructures not only to the ethnographic researcher, as argued by Karasti and Blomberg, but also to the historical actors, in this case furthering the knowledge exchange between the manufacturer of a technology and its users. The history of the “battle of the glasses” suggests that a lot may be gained from bringing the innovation and controversy studies literatures into closer conversation, starting from the premise that controversy is not just “creative abrasion,” or a minor inconvenience, but that it may change a user innovation community and its knowledge infrastructures quite profoundly.

Conclusion

In examining the “battle of the glasses” waged among microscopists in the 1870s, this chapter has brought insights from innovation studies to bear on the history of science and technology. The chapter has argued that the British amateurisation of the 1860s and 1870s was more than the formation of a new collective identity for amateurs engaging in scientific research. It also spurred the development of large-scale infrastructures for the exchange of scientific information and, crucially, the collaborative innovation of scientific instruments. While the RMS had already been founded in 1839, it was only in the 1860s that the society saw a rapid growth in membership. At around the same time, the RMS’ collection of scientific instru-

[135] Vertesi, "Seamful Spaces," 269.
[136] My understanding of the work done by Abbe and the RMS is backed by van Oost et al.’s observation that “innovative users are likely to perform … heterogeneous activities when bringing the various elements into line that are necessary for the development and stabilization of an innovation community and the innovations themselves.” Van Oost, Verhaegh, and Oudshoorn, "From Innovation Community to Community Innovation," 188.

ments was established, it was granted a Royal Charter, and the society became embedded in a growing network of microscopy societies linked through the exchange of publications and overlapping memberships. Drawing on the user innovation literature, the chapter has argued that the process of amateurisation afforded the emergence of an early user innovation community with its own moral conventions and knowledge infrastructures.

The aperture controversy, following Robert Tolles' 1871 report on his immersion lenses, put the British microscopy community and its knowledge infrastructures under pressure. The controversy was originally sparked by the question of whether an immersion lens could possibly have an angular aperture exceeding 82° in balsam, but the debate was bound up with the more general problem of what the ultimate limit of resolution was that could be achieved with a light microscope. The first years of the debate were dominated by a flurry of articles written by Tolles and his main opponent Francis Wenham and published in the RMS journal. The two adversaries and their supporters first resorted to ray diagrams to make their points, but as the debate wore on, they began to think of other ways of proving their opponents wrong, including witnessed experiments, photomicrographs and the numerical notation of how light travels through immersion lenses. In short, the aperture controversy helped to diversify the knowledge infrastructures of the RMS and facilitated the introduction of new conscription devices.

Since the aperture controversy was tied to the broader question of what the ultimate limit of resolution was, its dynamics changed after Ernst Abbe published his theory of microscopic vision, which included a calculation of the maximum resolving power of a light microscope. Abbe also suggested to replace angular aperture with numerical aperture, so the aperture of a lens could be measured independent of the immersion medium used. On the one hand, Abbe's theory further spurred the turn towards numerical notation, which some contemporary microscopists considered a more thorough theoretical approach to microscopy than the previous trial-and-error practices that had shaped the work of artisanal microscope manufacturers. On the other hand, as Feffer has demonstrated, Zeiss' workshop continued to rely on the craft knowledge of artisans, and this chapter has shown that Abbe's innovations in microscopy, too, benefitted from the practical skill of the British microscopists.

Reaching out to the RMS Fellows during the aperture controversy meant that Abbe became involved with the RMS at a time when their infrastructures were unsettled. The controversy had forced the RMS' ways of communication to diversify, allowing for practical demonstrations, collaborative letters, periodicals, photographs and diagrams to co-exist. For Abbe, this was an opportunity to engage with the RMS in various ways, but making those infrastructures work in unison, and to his advantage, required Abbe to engage in heterogeneous engineering.

Since Abbe was a skilled experimenter and familiar with classroom demonstrations, he adapted easily to the RMS' preference for witnessed practical demonstrations over theoretical treatises. Moreover, he found infrastructural allies in some of the RMS Fellows, who helped him navigate the knowledge infrastructures of the British microscopy community, for example by deliberating over Abbe's rebuttals to Wenham's published letters or asking him to make wallcharts to illustrate his theory.

Abbe profited from his exchanges with the RMS Fellows in multiple ways. The RMS made its collection of scientific instruments available to Abbe, as well as the private collections of its members, which proved to be an inspiration to the physicist and also made it possible for him to establish who deserved credit for an invention. The chapter has also shown that the mutual trust between Abbe and the Fellows acted as an additional appropriability strategy. The Fellows commissioned Abbe, instead of other manufacturers, to make instruments for them and at the same time provided him with information about his English competitors. The most marked success of Abbe's collaboration with the RMS was the homogeneous immersion lens he developed after Stephenson convinced him of its scientific benefit. Abbe first doubted that microscopists would find homogeneous immersion lenses convenient to use, but the success of the lenses among bacteriologists soon proved that Stephenson's innovation was not only an interesting scientific puzzle, but also an asset to bacteriological research.

Whereas the previous two chapters looked at the kinds of infrastructures microscopists built and used to learn how to observe microscope specimens and make permanent slides together, this chapter has been more concerned with how industrial science, here represented by Zeiss and Abbe's production of microscopes, profited from those infrastructures. The history of Abbe, the RMS and the "battle of the glasses" invites us to ask if there are other historical scientific communities we might want to reconceptualise as user innovation communities in order to acknowledge their innovative capacities and impact on the development of scientific instruments. Since it was spurred by the aperture debate, the exchange between Abbe and the RMS also suggests that controversy and user innovation sometimes go hand-in-hand, and that one may reinforce the other – a phenomenon that seems to deserve more attention from scholars in both controversy and innovation studies.

Despite the fruitful collaboration between Abbe and the RMS, by the end of the 1880s, it became hard to deny that the actors and organisations that had dominated the microscopy community from mid-century onwards were struggling to uphold their authority. Even if Zeiss continued to rely on the craft knowledge of his opticians, Abbe's calculations soon made it possible to mass-produce microscopes on an unprecedented scale, which put smaller manufacturers under pressure. The following chapter completes the historical narrative of this dissertation by drawing together the main insights and common threads of the previous chapters, providing answers to the question of how scattered microscopists acquired craft knowledge of microscopy, and discussing the apparent decline of the microscopy community towards the end of the nineteenth century. It concludes with a reflection on my own "infrastructuring" in researching the history of microscopy – and what that history may teach us about building knowledge infrastructures for participatory research projects.

5 "Observers Scattered All Over the World": Citizen Science in the Nineteenth and Twenty-First Centuries

> For now, doctoral students undertaking digital work in history have the unenviable task of straddling both worlds – the forms and structures designed for traditional monographs and the as yet minimally defined world of digital design, computational analysis, and digital production. And yet, it is the very lack of definition that makes it a particularly interesting and productive time to engage in digital scholarship.[1]

This final chapter is an attempt at "straddling both worlds." It concludes the historical narrative of the previous chapters and reflects on the "digital production" of my dissertation. The chapter revisits the main themes I set out to explore in the introduction and provides answers to the question of how geographically dispersed microscopists developed ways of sharing craft knowledge of microscopy, ranging from making observations and preparations to the production of scientific instruments. The chapter also looks at the decline of microscopy societies and their publications at the turn of the twentieth century, outlining some of the reasons why microscopists became less influential in the scientific community. After that, the chapter turns to my own infrastructural work in researching the history of microscopy: the web-based citizen science project I built and ran as part of my PhD. As long as a PhD in the humanities is awarded based on a linear text submitted as a PDF file, the work that goes into digital design and computational analysis can only be acknowledged when it is included in the written dissertation in some way.

Moreover, I would argue that concluding this dissertation with a reflection on the present and future of digital citizen science has wider scholarly merit, too. Dana Mahr and Jeremy Vetter, among others, have convincingly argued that it can be rewarding to bring a historical perspective to bear on today's citizen science projects.[2] As Vetter puts it, "placing the growing collection of recent examples of lay-expert interactions among a diverse set of historical examples … allows us to understand what is peculiar or distinctive about present-day configurations of how lay people are involved in scientific observation."[3] Inspired by such historically

[1] Jeri E. Wieringa, "Beyond the PDF: Navigating the Digital Dissertation," *The American Historian*, October, 2020, https://www.oah.org/tah/issues/2020/loss-and-learning/beyond-the-pdf-navigating-the-digital-dissertation/. Accessed on 11 August 2022.
[2] See J. Vetter, "Introduction: Lay Participation in the History of Scientific Observation," *Science in Context* 24, no. 2 (2011): 127-141; Dana Mahr, *Citizen Science: Partizipative Wissenschaft im späten 19. und frühen 20. Jahrhundert* (Nomos, 2014); Sally Shuttleworth and Berris Charnley, "Science Periodicals in the Nineteenth and Twenty-First Centuries," *Notes and Records: The Royal Society Journal of the History of Science* 70, no. 4 (2016): 297-304.
[3] Vetter, "Introduction: Lay Participation in the History of Scientific Observation," 127.

informed work on present-day citizen science, my own reflection on citizen science draws on my historical research into microscopy in the late nineteenth century. The protagonists in this dissertation were a very diverse group of microscopists – some, like Romyn Hitchcock, Vida Latham or Ernst Abbe, were trained scientists, whereas others, like Eugene Rau or Mary Ward, primarily considered microscopy a leisure pursuit. Despite their different backgrounds and training, these microscopists often collaborated quite successfully. I would argue, therefore, that conceiving of late-nineteenth-century microscopy as a historical case of lay-expert interaction – while considering the difference between historical and present-day concepts of expertise – can help us develop new strategies for building alliances between trained and untrained researchers, which is crucial for ongoing and future citizen science projects.

In examining the digital infrastructures of citizen science in the conclusion of this dissertation, I emphasise the performative dimension of studying (historical) knowledge infrastructures. As explained in the introduction, following the work of Karasti and Blomberg, infrastructure scholars are aware that they themselves "are engaged in constructing the field through the myriad of choices they make about what aspects … deserve their focus."[4] This, as Karasti and Blomberg further argue, asks for "studies of infrastructuring, i.e. the ongoing and continual processes of creating and enacting information infrastructures."[5] Wolfgang Kaltenbrunner regards the performativity of infrastructure studies as a "generative resource," an opportunity to imagine and build alternative infrastructures.[6] Reflecting on present-day infrastructures of citizen science and placing them in historical context may therefore help us address common challenges of citizen science projects and imagine these projects differently. For example, as I will show, the history of late-nineteenth-century microscopy is particularly useful in understanding the kinds of infrastructure needed to exchange qualitative observations, which may help us create web-based citizen science projects that make it possible to exchange more complex knowledge than quantitative data.

In the following, I first draw together the previous chapters to answer the question of how microscopists acquired craft knowledge, often without being able to meet in person and practice microscopy together. In doing so, I follow the main themes I set out to explore in the introduction – craft knowledge, infrastructure, community-building, and science education – and I show how these different dimensions of my dissertation provide insight into processes of knowledge exchange in the late nineteenth century. Then, I turn to microscopy around 1900, investigating the apparent decline of the microscopy community and placing it in

[4] Karasti and Blomberg, "Studying Infrastructuring Ethnographically," 234.
[5] Ibid.
[6] Kaltenbrunner, "Infrastructural Inversion."

the context of broader developments in science education, the scientific community, infrastructure, and craft knowledge at the turn of the twentieth century. Finally, I take my citizen science project as a vantage point to look at the resurgence of lay-expert partnerships in the digital age, drawing on the past to imagine alternative digital infrastructures and future models of collaboration.

Learning Microscopy at a Distance in the Late Nineteenth Century

Craft Knowledge and Infrastructure

As outlined in the introduction, this research started from the premise that working with a microscope required a kind of craft knowledge that was difficult to teach and learn without personal instruction. Late-nineteenth-century microscopists themselves observed that the use of the microscope in making observations, the production of microscopes, as well as the making of slides and other accessories required knowledge that could not always be found in books.[7] Microscopy asked for a steady hand and care in handling microscopes and microscopic objects, skill in working with varying mounting ingredients in different climatic conditions, as well as the ability to interpret what was seen through the microscope. For a long time, historians of science tended to argue that acquiring craft knowledge depended on on-site interaction among artisans, but a few scholars have begun to explore alternative ways of craft knowledge exchange in the early modern age and beyond.[8] The previous chapters have helped to expand that literature by showing that microscopists' long-distance knowledge exchange was intimately linked to the emergence of new trade and communication infrastructures in the second half of the nineteenth century.

Following the travels of rotifer illustrations, Chapter Two has shed light on the role of the burgeoning print culture in sharing observations. Microscopists used illustrations as "working images," as a way of observing microscope specimens closely by sketching them.[9] I argued that to some extent, illustrations remained working images even after their publication, as they were reproduced through scissors-and-paste practices, which were on the rise in the nineteenth-century periodical market.[10] Microscopists learned to observe not just by sketching a specimen, but also by copying illustrations of that specimen, as the sketchbook of Thomas Bolton's son shows. Reproductions of illustrations thus entered new contexts of observation and became associated with different observational

[7] See Osborn, "Editorial – Postal Microscopical Clubs."
[8] See, for example, Hausse, "The Locksmith, the Surgeon, and the Mechanical Hand;" Dupré, "Doing It Wrong;" David Kaiser, Kenji Ito, and Karl Hall, "Spreading the Tools of Theory: Feynman Diagrams in the USA, Japan, and the Soviet Union," *Social Studies of Science* 34, no. 6 (2004): 879-922.
[9] See Nasim, *Observing by Hand*.
[10] See Pigeon, "Steal It, Change It, Print It."

practices as they were reprinted. In Mary Ward's microscopy handbook, Philip Henry Gosse's illustration for the Royal Society was adapted to domestic practices of observation and became entangled with the repurposed household items that Ward used to keep and observe microscopic animals. Notably, Gosse's rotifer illustrations were distributed widely not only within the burgeoning print market for scientific publications, but also with the help of novel at-home printing presses, like those used and sold by Thomas Bolton in Birmingham and Jules Pelletan in Paris. Microscopy suppliers like Bolton and Pelletan were able to provide their subscribers with cheap, home-made illustrations, and at the same time guide their observation of microscope specimens.

Bolton and Pelletan's prints were part of a broader trend of making and circulating so-called manuscript magazines, handwritten magazines shared among a select group of reader-contributors. Manuscript magazines also inspired the foundation of the British Postal Microscopical Society and, later, the American Postal Microscopical Club, which circulated handwritten notes alongside microscope slides.[11] In those postal microscopy associations, craft knowledge of slide making came to be entwined with the members' skill in using and shaping the postal system to their advantage. From its inception, the American Postal Microscopical Club not only depended on the postal system but actively changed it, as demonstrated by its successful 1878 petition to allow for the mailing of glass. The amendment of the postal law laid the groundwork for a postal system that facilitated the mailing of scientific trade items. Over time, the club's chain-letter network itself became a long-term experiment to test the durability of slides. The chapter on postal slide exchange has also exposed some of the strategies microscopists developed to learn how to make microscope slides without being able to meet and practice together, such as the reverse-engineering of possible causes of damage.

As the fourth chapter has shown, craft knowledge continued to be vital in the production of microscopes, too, despite the growing rhetoric of scientisation around Zeiss' microscopes in the 1880s. Although microscopes were constructed based on Ernst Abbe's calculations, which sought to put an end to trial-and-error practices of making and combining microscope lenses, there were very few men in Zeiss' workshop who possessed the manual skill necessary to make the new instruments. Moreover, Abbe's inventions drew on ideas he developed through his correspondence with the Fellows of the RMS. The Fellows tinkered with microscopes and accessories as they reproduced Abbe's experiments, and they conceived of new instruments, as well as new ways of using the instruments developed by Abbe. Building on Sam Alberti's notion of "amateurisation," the

[11] One of the founders of the British Postal Microscopical Club, Alfred Atkinson, explained in *Science Gossip* that his idea of a postal microscopy society was inspired by manuscript magazines. See Atkinson, "Microscopic Postal Cabinets."

chapter has also shown that the Fellows helped Abbe understand the knowledge infrastructures built by the RMS and other British natural history societies in the second half of the nineteenth century, so that Abbe could better navigate them from afar.[12] The controversy surrounding immersion lenses and the ultimate limit of resolution in a microscope multiplied the infrastructures available to Abbe and the Fellows. The "battle of the glasses" prompted the microscopists involved in it to conceive of ever-new ways of proving their opponents wrong and impacted their conscription devices, as geometrical line drawings were supplemented with calculations and photomicrographs.

Microscopists thus profited from sprawling national and international postal systems, including the introduction of postal reforms, new printing technologies and photomicrographs, as well as a steep rise in the number of illustrated handbooks and scientific periodicals with their participatory correspondence columns. To share their "practical knowledge" of microscopy, microscopists began to use late-nineteenth-century infrastructures to their advantage, circulating slides, illustrations, as well as living specimens, and conceiving of various ways of long-distance collaboration.[13] In the process, microscopists themselves helped to build infrastructures which facilitated the exchange of craft knowledge.

Community-Building

As infrastructure scholars have long shown, infrastructures are not only built by, but also shape, the communities interacting with them.[14] The previous chapters have therefore also shed light on community-building in the late nineteenth century, moving from a very loose network of illustrator-copiers, connected mainly by scissors-and-paste practices, to a closer but virtual community of postal society members, and finally to the more intimate relationship between Abbe and the RMS Fellows, which involved regular correspondence and occasional meetings. Since the largely virtual communities of illustrators and postal society members were more accessible than the RMS, they were considerably more diverse, making it possible for microscopists living in remote areas, as well as women and disabled microscopists, to exchange observations and meet people with similar interests. Therefore, on a methodological level, this dissertation serves as a reminder that our notion of what makes a scientific community determines which historical actors are included in our analyses, and that a turn towards virtual communities, coming together with the help of postal networks or on the pages of

[12] See Alberti, "Amateurs and Professionals in One County."
[13] "Practical knowledge" was the term used by the *Scientific American* to describe microscopists' skill in "The Manufacture of Scientific Apparatus."
[14] See, for example, the "communities of practice" described in Star and Ruhleder, "Steps toward an Ecology of Infrastructure." This is explained in more detail in the introduction.

books and periodicals, allows us to consider more diverse groups of scientific practitioners.[15]

In tracing the circulation of rotifer illustrations, Chapter Two has argued that copying illustrations was a citational practice which allowed illustrators to adapt illustrations to their own observational work, and thus associate both new ways of observing and new kinds of observers with microscopy. Illustrations were crucial in the formation of a social identity for microscopists and their community-building: copying and thereby changing illustrations invited new groups of observers to take up microscopy and consider themselves microscopists. The illustrations in Slack's book, showing specimens at one focus only, made microscopy accessible to observers who could not afford to buy expensive instruments. Clara Kern Bayliss' imaginative microscopy book helped to recruit schoolchildren to microscopy, whereas Mary Ward's illustrations of repurposed household items helped to embed rotifer research in women's domestic lives.

The British Postal Microscopical Society and the American Postal Microscopical Club reached into their members' homes, too. Members examined the circulated slides at home, which enabled their family members, servants and housemaids to engage with microscopy. The two postal organisations allowed marginalised groups of microscopists to be part of a virtual community of slide makers. The postal nature of the two organisations made them more accessible, but also vulnerable to disruptions caused by slide breakages and unreliable members. Whereas the British Postal Microscopical Society made its organisation more robust by encouraging members to form subgroups and meet in person if possible, the American Postal Microscopical Club mainly relied on microscopy journals to discipline its members and keep track of the circulation of slides. Microscopy periodicals, as a mechanism of one-to-many communication, became vital to the functioning of the American Postal Microscopical Club.

During Abbe's collaboration with the RMS Fellows, the society's microscopy periodical played a similar role as the periodicals that reported on the activities of the American Postal Microscopical Club, broadcasting the scientific findings and technological innovations of its Fellows to the rest of the society. Considering the RMS Fellows as an early form of a user innovation community, the fourth chapter has shown that the RMS journal helped to connect microscopists in Great Britain and beyond, and that it facilitated the exchange of ideas for the development and use of microscopes and all sorts of microscopy accessories. The fourth chapter has argued for the importance of infrastructure in the process of amateurisation in Great Britain, providing a fresh perspective on the role of user communities in the emergence of industrial science in the late nineteenth century. It has shown that, at least in the case of the Zeiss company, industrial science

[15] This turn is discussed in more depth in Dawson et al., *Science Periodicals in Nineteenth-Century Britain*.

benefitted from the infrastructures built by microscopists, with the RMS Fellows providing Abbe with both companionship and innovative ideas. The chapter thus confirms Andreas Daum's argument that nineteenth-century natural history societies were "local centres which generated international networks" with the help of society publications, travelling lecturers, as well as associated natural history collections.[16] Crucially, these international networks connected not only diverse groups of scientific practitioners, as Daum and others have shown, but also facilitated collaborations between technology users and manufacturers from abroad.

Science Education

According to Feffer, Abbe owed some of his skill in fashioning public demonstrations of his theory of microscopic vision to the teacher training that was part of his studies at Göttingen.[17] In the previous chapters, it has become clear that this was by far not the only instance where the knowledge infrastructures of microscopy and science education intersected. In fact, the history of crafting knowledge infrastructures for microscopy in the late nineteenth century is at the same time a history of growing attention for (and the professionalisation of) education in the life sciences. Although this dissertation has not discussed how microscopy was taught in the context of formal school or university education, it has put the historical actors centre stage who supplied educational institutions with teaching materials – illustrators, slide makers, and microscope producers.

We have seen that rotifer illustrations moved between formal and informal science education. Philip Henry Gosse's *Evenings at the Microscope* and Mary Ward's *A World of Wonders Revealed by the Microscope* were aimed at beginners in microscopy studying from home, just like Clara Kern Bayliss' *In Brook and Bayou.* Kern Bayliss' book, however, came to be read in the classroom and on school excursions. Charles Thomas Hudson turned his and Gosse's rotifer illustrations in *The Rotifera* into educational backlit transparencies for science demonstrations at society meetings. And in the hands of Thomas Bolton, the same rotifer illustrations became rough sketches and prints that were distributed to educational institutions through a subscription service for living microscope specimens. Bolton also circulated manuals on how to observe his specimens, which demonstrates that natural history dealers also provided teachers with advice on how to use their educational materials.

[16] Andreas W. Daum, "'The Next Great Task of Civilization': International Exchange in Popular Science. The German-American Case, 1850-1900," in *The Mechanics of Internationalism: Culture, Society, and Politics 1850-1914*, ed. Martin H. Geyer and Johannes Paulmann (Oxford: Oxford University Press, 2001), 315.
[17] See Feffer, "Ernst Abbe."

In the case of the two postal microscopy organisations discussed in this dissertation, the rise of education in the life sciences played an important role, too. The American editor John Phin, himself a member of the American Postal Microscopical Club, appealed to his readers to acknowledge the value of objects – and microscope slides in particular – in science education, instead of regarding the reading of texts as the hallmark of a thorough education. Phin's views on science education were aligned with a broader trend towards studying nature through material objects that children would find in their local surroundings, a development which culminated in the American nature study movement.[18] The long-standing inclination of the American government to support the distribution of educational materials through the post made it easier for members of the postal microscopy club to make a case for sending microscope slides through the mails. In Great Britain, too, scientific classroom teaching became oriented towards providing children and university students with material objects. Like Bolton's preparations, the slides of both the British and American postal microscopy organisations were circulated to schoolteachers, and there is evidence that teachers observed the slides in the classroom together with their pupils.[19]

Clearly, in the 1870s and 1880s, formal education in the life sciences, in schools, universities and museums, was bound up with the more informal knowledge infrastructures built by microscopists on both sides of the Atlantic.[20] Microscopy societies advocated for science education, just like other scientific organisations, as Jennifer Tucker and others have shown.[21] They also helped to produce and circulate the materials needed to deliver a sound scientific education that was at least as much based on the observation of specimens as the close reading of texts. Specimen dealers and slide makers, of course, were equally keen to provide educational institutions with objects. Science education reforms thus initially helped to invigorate the production of educational scientific objects, offering craftspeople a business opportunity which allowed them to hone their skills and pass on their knowledge of microscopy.[22] Overall, the history of microscopy told in this dissertation illustrates that by bringing business history and the history of education into closer conversation with the history of science, we can better acknowledge the importance of craftspeople beyond the early

[18] See Kohlstedt, *Teaching Children Science*.
[19] See Ward, "Report of the American Postal Microscopical Club."
[20] Looking at the case of the Kew Museum of Economic Botany, Laura Newman and Felix Driver write that the museum supplied schoolteachers with natural history objects, which became a very popular scheme. In fact, sometimes demand seems to have outstripped supply, which may have helped Bolton to establish his business. Newman and Driver, "Kew Gardens and the Emergence of the School Museum in Britain, 1880–1930."
[21] See Jennifer Tucker, "Science Institutions in Modern British Visual Culture: The British Association for the Advancement of Science, 1831-1931," *Historia Scientiarum: International Journal of the History of Science Society of Japan* 23, no. 3 (2014): 191-213.
[22] See also Nick Hopwood's study of late-nineteenth-century collaborations between scientists and wax modellers, Hopwood, *Embryos in Wax*.

modern period, which has long been the focus of scholarship dealing with the production of craft knowledge.

By the turn of the twentieth century, however, the influence of microscopists and microscopy societies on science education, and the scientific community more broadly, had started to wane. In the late 1880s and 1890s already, microscopists began to lament the declining numbers of society members, and by the turn of the twentieth century, most microscopy periodicals had ceased to exist.[23] The next section examines the reasons for the decline of the microscopy community, turning to broader developments in scientific craft and infrastructure, the scientific community, and science education at the turn of the century.

Microscopy Around 1900

Whereas the 1870s and early 1880s had seen a steep growth in the number of European and American microscopy societies, periodicals, microscope manufacturers, and commercial slide makers, by the 1890s, it was clear that the tide had started to turn. In 1897, Charles Smiley, editor of the *American Monthly Microscopical Journal*, lamented "the greatly decreased number of local societies and the loss of interest in their work throughout the country."[24] When we look at the changing title, content, and envisioned readership of Smiley's and many other microscopy journals, we can begin to understand how the microscopy community, and its position relative to the broader scientific community, changed towards the end of the nineteenth century. The first English and American microscopy periodicals were closely associated with microscopy societies, but they were soon joined by journals which either targeted a broader readership interested in natural history more generally, like the *American Journal of Microscopy and Popular Science*, or turned to specialist groups, for example medical practitioners and bacteriologists, like Louisa Reed Stowell and Charles Stowell's *The Microscope*.[25] Moreover, periodicals like W. Queen & Co.'s *Microscopical Bulletin* and Bausch & Lomb's *Journal of Applied Microscopy*, founded in 1883 and 1898, respectively, testify to the growing influence of a few big microscope manufacturers. Both periodicals were to a large extent trade catalogues, combining adverts with advice on how to use the manufacturers' products. Hence, the changing periodical market reveals an increasing fragmentation of microscopy readerships, and a commercialisation of microscopy publications.

[23] See Brock, "Patronage and Publishing."
[24] Smiley, "Editorial," 260.
[25] Medical practitioners also began to found their own microscopy societies, or subgroups within existing societies, which further increased the fragmentation of the microscopy community. For example, Jabez Hogg, a physician and RMS Fellow, founded London's Medical Microscopical Society in 1873.

Donald Padgitt's overview of American microscope manufacturers confirms that whereas in the 1870s and early 1880s, new companies emerged at a rapid pace, towards the end of the nineteenth century the production of microscopes came to be dominated by just a few big companies which increasingly mass-produced microscopes.[26] Gerard Turner sees a similar trend in the European market at the time.[27] Likewise, commercial slide makers, who, from the mid-nineteenth century, had founded microscopy supply businesses to provide educational institutions with slides and microscopy equipment, were gradually put out of the market by educational suppliers with a broader range of products.[28] The commercialisation of microscopy was intertwined with the professionalisation of the life sciences and science education, as the mass-production of microscopes was fuelled by a surging demand for microscopes in laboratory science at universities and in industry.

As microscopy moved into formal university education, its ties to microscopy societies with their many self-taught members weakened. Science professionalisers like Thomas Huxley acknowledged the work done by microscopy societies, but they made it very clear that microscopists without formal training could only hope to support professional scientists in their work in the future.[29] Moreover, as Susan Leigh Star has shown for taxidermy around 1900, the professionalisation and industrialisation of biology led to a devaluation of informal science education and some forms of craft knowledge.[30] Star argues that "[those] parts of a craft skill which cannot be industrialized, formalized, or assimilated in the work of the professionals split off from the scientific part of the enterprise and came to be seen as merely educational or decorative."[31] In the case of microscopy, too, the do-it-yourself ethos of societies, and members' pride in their craft skill, lost value with the rise of industrial science, which sought to codify craft knowledge. Even though the production of microscopes continued to require craft knowledge, Abbe's calculations made it seem as if much of the skill needed to make microscopes could be expressed in equations.[32]

Moreover, as the historian of science John Warner argues, microscopists themselves were increasingly torn over what their role in the scientific community should be.[33] Some complained about the growing popularity of society soirees, which they felt had become crowded events with sensationalist displays that left little room to carefully examine specimens in-depth. Others suggested that microscopy societies should have at least a few members who were "professional

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[26] See Padgitt, *A Short History of the Early American Microscopes*.
[27] See Turner, *Essays on the History of the Microscope*.
[28] See Karlheinz A. Rosenbauer, *Mikroskopische Präparate. Hersteller und Lieferanten. Eine Zusammenstellung aus zwei Jahrhunderten*, vol. 1 (Darmstadt: GIT Verlag, 2003).
[29] See Huxley, "The President's Address."
[30] Star, "Craft vs. Commodity," 258.
[31] See Star, "Craft vs. Commodity."
[32] See Feffer, "Ernst Abbe."
[33] See Warner, "'Exploring the Inner Labyrinths of Creation'."

scientific men" and could organise the society in such a way that it would facilitate systematic research.[34] Just as microscopy publications struggled to attract a broad readership and began to target more specialised professionals, microscopy societies also wrestled with the specialisation and compartmentalisation of microscopy. For a long time, members of microscopy societies had prided themselves on bringing together "mathematicians, physicists, chemists, and zoologists, the teacher of natural science, and the physician, the technologist and the amateur who finds in scientific pursuits relaxation from other occupation," as John Matthews, president of the RMS, asserted in 1876.[35] The president of London's Quekett Microscopical Club, however, found in 1880 that "we are hopelessly specialised, both as to our modes of thinking, as well as upon the general subject-matter of our thoughts."[36] As more and more scientific disciplines adopted the microscope as an indispensable research tool, it became more difficult for societies to contain the diverging interests of their members, and offer discussions and activities that appealed to all, or many of them.

By the end of the nineteenth century, beginners in microscopy also had to cover more ground than a few decades earlier before they could make contributions of value to the field of research they were interested in.[37] In the mid-nineteenth century, when the microscope was still finding its place in many research domains such as geology or forensics, it had been easier for beginners – and generalists – to contribute to discussions in many fields. This became harder after microscopy was firmly integrated in a research field and a whole stock of knowledge developed around it, as well as discipline-specific practices of using a microscope. Beginners were also less likely to contribute to scientific research using comparatively cheap instruments. Achromatic compound microscopes had become the de facto standard in scientific research by the mid-nineteenth century. Simple microscopes could be purchased more cheaply, but some manufacturers seem to have overpromised what could be accomplished with such instruments. In his beginners' guide to microscopy, the editor John Phin warned his readers that "the operations of certain parties, too well known to the public, have brought a certain degree of suspicion upon all attempts to popularize this most valuable instrument."[38]

In addition to these developments in science and technology, microscopy was also affected by profound changes in the visual culture, and media landscape, of the late nineteenth century. This dissertation has not discussed nineteenth-

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[34] "Microscopical Societies," *American Monthly Microscopical Journal* 5 (1884): 237.
[35] John Matthews, "President's Address," *The Journal of the Quekett Microscopical Club* 4 (1876): 189.
[36] Thomas Spencer Cobbold, "The President's Address," *The Journal of the Quekett Microscopical Club* 6 (1879-81): 177.
[37] See Warner, "'Exploring the Inner Labyrinths of Creation'."
[38] John Phin, *How to Use the Microscope*, 5th ed. (New York: The Industrial Publication Company, 1882), ix. Phin is also cited in Warner, "'Exploring the Inner Labyrinths of Creation'."

century ways of seeing in much depth, but we need to factor in the changing visual landscape, and in particular the rise of photography, if we want to understand the gradual decline of the microscopy community. From the beginning, photography had been closely linked to microscopy, with the chemist Humphry Davy using a solar microscope to make photographic enlargements at the beginning of the nineteenth century.[39] But it was only after the introduction of dry plates in the 1870s that photomicrographs had high enough resolution to capture the details of a microscope specimen.[40] The subsequent turn to photomicrography also had an impact on scientists' way of seeing. As Stefanie Dufhues argues, Robert Koch came to believe that photomicrographs offered more scientific insight into a specimen than the microscope slides he observed.[41] Photography did not altogether replace permanent slides or manual drawings in microscopy, but as photographs became cheaper to reproduce and circulate, they put economic pressure on slide makers, some of whom retrained as photo(micro)graphers.[42] Possessing the necessary skills to make permanent slides, once a mark of distinction for any microscopist, became less important when photomicrographs could be used to quickly capture a specimen on paper.

Warner sees another reason for the decline of the microscopy community in the closer association of microscopy with disease that came with the advent of bacteriology in the last two decades of the nineteenth century. According to him, "this face of nature was less appealing than an earlier one represented by curious animalcules, and plainly was less desirable as a recreational outlet."[43] The literary scholar Martin Willis confirms that there was a link between microscopy and contagion in the public imagination.[44] However, Warner's argument seems less convincing when we consider that microscopists had seen beauty in things others found unappealing or even disgusting throughout the nineteenth century, and that shocking viewers was often as much part of the spectacle of microscopy as enticing them. For example, the horror viewers felt at seeing cheese mites for the first time was a common trope in microscopy writing, while the microorganisms that populated the Thames had caused public outrage and sanitary concerns as early as 1828 (Fig. 5.1). Maybe the rise of bacteriology did help to forge a stronger link between microscopy and contagious disease in the public mind, but above all it firmly placed microscopy in the scientific laboratory, which, besides providing

[39] See Gerard L'E. Turner, "Microscopical Communication," *Journal of Microscopy* 100, no. 1 (1974): 3-20.
[40] See Stefanie Dufhues, *Fotografie Konstruierter Sichtbarkeit: Bildpraxis der Mikrofotografie von den ersten Versuchen bis ins 20. Jahrhundert* (Leiden: Brill, 2020).
[41] See Dufhues, *Fotografie Konstruierter Sichtbarkeit*.
[42] Ibid.
[43] Warner, "'Exploring the Inner Labyrinths of Creation'," 32.
[44] See Willis, *Vision, Science and Literature, 1870-1920: Ocular Horizons*.

better-controlled experimental conditions, regulated who could access and carry out scientific research.[45]

Figure 5.1 A woman dropping her porcelain tea-cup in horror upon discovering the monstrous contents of a magnified drop of Thames water; revealing the impurity of London drinking water. Coloured etching by W. Heath, 1828. CC BY-NC 4.0 Wellcome Collection.

Towards the end of the nineteenth century microscopists also grappled with a challenge to their role in the construction of scientific instruments. When the RMS was founded in 1839, it set down in its rules and regulations that its main objective was the "advancement" of microscopy. On the one hand, this meant that the RMS Fellows sought to encourage the use of the microscope in the sciences and enlist societal support for microscopy. On the other hand, the Fellows were just as determined to further develop the microscope and all sorts of microscopy equipment. The French microscopist and editor Pelletan was convinced that microscopists, in trying to observe ever smaller organisms, had helped to push the limit of resolution in light microscopes.[46] Indeed, as the previous chapter has shown, microscopists shared a competitive spirit of trying to push the resolving power of objectives. But after Abbe and Helmholtz calculated the limit of microscopic vision in the 1870s and gradually approached it with the help of homogeneous immersion lenses and new kinds of glass in the 1880s, microscopy societies lost one of their *raisons d'être* – the resolution in light microscopy could

[45] For a study of the history of the lab-field border, see Robert E. Kohler, *Landscapes and Labscapes: Exploring the Lab-Field Border in Biology* (Chicago: University of Chicago Press, 2002).
[46] See Pelletan, "Revue."

not be pushed much further.[47] Moreover, as Feffer has shown, Zeiss' instruments redefined what counted as good performance: "the best systems were not the ones that resolved the smallest objects, but the ones that provided the best all-around definition."[48]

Finally, it seems worth returning to the user innovation literature in order to understand how the microscopy community changed at the end of the nineteenth century. User innovation scholars have shown that user innovation communities tend to be very dynamic, as they are affected by the different stages of the innovation process and grow (or decline) alongside a new technology.[49] Von Hippel has found that the formation of user innovation communities is particularly rewarding for manufacturers and users when a new technology is introduced and there are comparatively few, widely distributed users with heterogeneous needs.[50] Around the mid-nineteenth century, when microscopy was gaining popularity in medicine and the life sciences but was not as wide-spread a method as it would be by the end of the century, microscopy societies proved to be a fertile environment to bring microscopists together, exchange ideas about possible uses of the microscope, and, last but not least, form a critical mass of potential clients for microscope manufacturers.

By the end of the nineteenth century, however, microscopy had become a common method in many scientific fields, including geology, archaeology and even palaeography.[51] Conversations about the use of the microscope moved into these separate fields, where microscope users found like-minded practitioners with similar needs more easily than in the mid-nineteenth century. At the same time, the mass-production of microscopes spurred the standardisation of instruments, and custom-made instruments became less and less common. Microscopy became so well integrated (and standardised) in scientific research that microscope users rarely thought of themselves as "microscopists" anymore and did not feel as connected to a community organised around the technology as in the mid-nineteenth century. If, as Mody argues, we can think of an instrumental community as "a network of individuals who view their involvement with a particular type of instrument and/or instrumentality as ratifying their connection to other nodes in the network," then that sense of community was largely lost

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[47] One might argue that ultraviolet microscopy pushed the limit further in the twentieth century, but Abbe and Helmholtz' calculations put an end to the search for the theoretical limit of resolution in light microscopy.

[48] Feffer, "Ernst Abbe," 54.

[49] See Shah and Mody, "Creating a Context for Entrepreneurship;" Christoph Hienerth, "The Commercialization of User Innovations: The Development of the Rodeo Kayak Industry," *R&D Management* 36, no. 3 (2006): 273-294.

[50] See von Hippel, *Democratizing Innovation*.

[51] See Josephine Musil-Gutsch and Kärin Nickelsen, "Ein Botaniker in der Papiergeschichte: offene und geschlossene Kooperationen in den Wissenschaften um 1900," *NTM Zeitschrift für Geschichte der Wissenschaften, Technik und Medizin* 28, no. 1 (2020): 1-33.

among microscope users by the end of the nineteenth century.[52] Or, as Warner writes, microscopy "achieved its scientific maturity during the second half of the nineteenth century, but it also lost its identity as an autonomous science."[53] One might conclude that the microscopy community that had grown over the second half of the nineteenth century lost ground in a changing, more fragmented and specialised scientific landscape. Yet we must not forget that microscopy societies had set out to promote microscopy, a goal that had certainly been achieved by the turn of the twentieth century – even if it came at the cost of excluding self-taught generalists from microscopy as it was practiced in professional scientific disciplines.

Imagining Citizen Science in the Twenty-First Century

Most microscopy societies ceased to exist before or around 1900. Some, however, managed to draw members throughout the twentieth century, and some, like the British Postal Microscopical Society, the Quekett Microscopical Club, the RMS, or the American Microscopical Society, still exist today. The British Postal Microscopical Society continues to follow its original nineteenth-century model of circulating slides and notes, but other societies had to reinvent themselves to some degree in order to attract new members and continue their work. The RMS, partnering with the British Joint Committee for Electron Microscopy, became "closely involved in co-ordinating electron and light microscopy" in Britain and Europe, while the American Microscopical Society strengthened its profile as a society targeting professional scientists with an interest in invertebrate biology.[54] The Quekett Microscopical Club, on the contrary, cultivated an image as an organisation for amateur microscopists, providing educational resources for anyone interested in microscopy. By their own account, it was only in 2016 that members of the Quekett Microscopical Club started their "first large-scale venture into recording living specimens…, monitoring the spread of the invasive fruit-fly *Drosophila suzukii* (Matsumura) in the United Kingdom."[55] A year later, the club's website featured a "Citizen Science" category, showcasing a growing number of scientific projects initiated by members, sometimes in collaboration with professional scientists or scientific institutions.[56]

The scientific projects the Quekett Microscopical Club has participated in since 2016 are indicative of a broader trend towards citizen science initiatives

[52] Mody, *Instrumental Community*, 10.
[53] Warner, "'Exploring the Inner Labyrinths of Creation'," 32.
[54] See John L. Hutchison, *Moving Forward. The Royal Microscopical Society 1989-2014* (Oxford: The Royal Microscopical Society, 2014).
[55] See "Citizen Science," *The Quekett Microscopical Club*, http://www.quekett.org/. Web page captured on 21 July 2017. Accessed via the Internet Archive, https://archive.org/, on 16 June 2022.
[56] Ibid.

beginning at the turn of the twenty-first century, when professional researchers started to involve untrained volunteers in their research to solve big data problems. For example, SETI@home, now an indispensable part of the origin myth of citizen science, was an immensely popular project set up in 1999 by researchers of the Berkeley SETI Research Center to search radio signals for signs of extra-terrestrial life. The researchers crowdsourced computing capacities by having data analysed off-site on Internet-connected personal computers.[57] The advent of Web 2.0 platforms in the early 2000s gave new impetus to such crowdsourced data analyses, which moved from volunteer computing towards more participatory citizen science. Citizen science continued to use the computing power of citizen scientists' personal computers but also sought to involve untrained researchers in collaborative research projects.[58] As Sally Shuttleworth and Berris Charnley observe, in some ways the rise of citizen science is reminiscent of the nineteenth-century collaboration between formally trained and untrained researchers – both are stories of "new technologies facilitating new platforms and new types of communication."[59] And in both cases new platforms were used to connect geographically distant researchers.

Since 2009, the Zooniverse web platform has become home to many citizen science initiatives, providing the digital infrastructure for researchers to design and run collaborative research projects. Between 2009 and 2019, the Zooniverse hosted 229 projects, including the *Worlds of Wonder* project developed as part of this PhD.[60] From April 2019 to April 2020, *Worlds of Wonder* invited citizen scientists to identify and classify illustrations in nineteenth-century microscopy publications, describe what they saw in those illustrations, and transcribe the names of illustrators if possible. Underlying the project was the assumption that by classifying microscopy illustrations we would gain a better understanding of who had produced them and where they had travelled, ultimately making it possible to reconstruct some of microscopist's knowledge infrastructures. The idea was that the project data would make it possible to find reproductions of illustrations by searching for recurring illustrator names and pictorial content, and the citizen scientists were explicitly asked to look for and flag reproductions too. Around 2,400 volunteers helped to analyse just under 20,000 pages of material for *Worlds of Wonder*.[61] The collected data made it possible to visualise collaborations between illustrators, engravers and printers, and identify

[57] See Élise Tancoigne and Jérôme Baudry, "La tête dans les étoiles? Faire sens de l'engagement dans le projet de science participative Seti@Home," *Réseaux* 214-215, no. 2 (2019) : 109-140.
[58] See Ridge, "Crowdsourcing Our Cultural Heritage: Introduction."
[59] Shuttleworth and Charnley, "Science Periodicals in the Nineteenth and Twenty-First Centuries," 2.
[60] See "Zooniverse: 10 Years of People-Powered Research," Oxford University, 2019, https://www.ox.ac.uk/news/2019-12-12-zooniverse-10-years-people-powered-research. Accessed on 11 August 2022.
[61] For an explanation of how the publications were selected, see Chapter One. A list of all publications classified can be found in Appendix B.

the most prominent names. The data also facilitated the search for reproductions of rotifer illustrations and thus provided me with visual historical sources for Chapter Two.

Since its rise in the 2000s, citizen science has been praised for its potential to help form new alliances between science and civil society, but it has also faced severe criticism. Its critics consider citizen science just another form of exploitation of labour, since citizen scientists work without remuneration and, as Philip Mirowski writes, there is a risk that the data produced through their free labour are siphoned off by for-profit entities.[62] Moreover, citizen science may in fact widen the gulf between professional and amateur researchers, as most citizen science projects are hierarchical in their division of labour, assigning citizen scientists only very repetitive micro-tasks.[63] Organisers of citizen science projects have responded to such criticism by involving volunteers in all stages of the research process, including the overall design of the research project, data collection and analysis, and making their research results accessible to all participants.[64] However, increasing participation often requires more training of volunteers, which, as Mirowski further argues, may ultimately lead to a (rather paradoxical) professionalisation of citizen science.[65]

Initially, web-based citizen science was most often used in STEM-related research, but today it is becoming more firmly embedded in the humanities as a research method, so much so that "citizen humanities" has become an established term.[66] Like citizen science, the rise of citizen humanities has fuelled hopes for more public involvement in research, but it has also been met with criticism. Especially web-based citizen humanities projects have been subject to criticism that is commonly made against digital humanities more generally – the risk of datafication. As Kaltenbrunner writes, there is a fear that "a new form of digital positivism … is tacitly imported together with datacentric methods and tools for quantitative analysis."[67] Yet forging a closer alliance between citizen science and the humanities is essential in addressing some of the criticism made against current forms of citizen science, since humanists – and historians of science in

[62] See Philip Mirowski, "The Future(s) of Open Science," *Social Studies of Science* 48, no. 2 (2018): 171-203.
[63] See Philip Mirowski, "Against Citizen Science," Aeon, 2017, https://aeon.co/essays/is-grassroots-citizen-science-a-front-for-big-business. Accessed on 11 August 2022.
[64] See also Dana Mahr and Sascha Dickel's call for more autonomous, uninvited citizen science in "Citizen Science Beyond Invited Participation: Nineteenth Century Amateur Naturalists, Epistemic Autonomy, and Big Data Approaches Avant La Lettre," *History and Philosophy of the Life Sciences* 41, no. 4 (2019): 41.
[65] See Mirowski, "Against Citizen Science."
[66] See Barbara Heinisch et al., "Citizen Humanities," in *The Science of Citizen Science*, ed. Katrin Vohland et al. (Cham: Springer International Publishing, 2021), 97-118.
[67] Kaltenbrunner, "Infrastructural Inversion," 8-9. See also Johanna Drucker, *Speclab: Digital Aesthetics and Projects in Speculative Computing* (Chicago: University of Chicago Press, 2009).

particular – are well equipped to recognise a positivist approach to data analysis and propose alternatives.

Digital humanists are aware that web-based crowdsourcing projects which seek to generate machine-readable data tend to leave little room for the kinds of analysis more commonly associated with the humanities: the critical thinking, narration and interpretation that cannot be expressed in binary code. Some citizen humanities projects have managed to make room for critical analysis by designing their own digital infrastructures.[68] However, designing workflows from scratch is not an option for small projects with less funding and fewer researchers, which rely on platforms like the Zooniverse to set up workflows and recruit volunteers. Taking my own *Worlds of Wonder* project as a case in point, the rest of this chapter examines to what extent citizen science platforms like the Zooniverse may allow for an exchange of non-machine-readable knowledge, which I consider a crucial component of future web-based participatory research.

In doing so, I draw on the history of microscopy told in this dissertation. As Sally Shuttleworth writes, "[the] term 'citizen science' is obviously anachronistic when applied to the nineteenth century, but used as a lens, or heuristic tool, it has helped us to ask questions, and to develop areas of focus, which we might otherwise have neglected."[69] I would argue that, similarly, we can turn to the history of microscopy as a heuristic tool to reimagine models of lay-expert collaboration. The history of microscopy reminds us that both citizen science and citizen humanities projects would benefit from building infrastructures for qualitative knowledge exchange. Since microscopists shared qualitative rather than quantitative observations and even conceived of ways of sharing craft knowledge at a distance, the history of microscopy can serve as an inspiration to imagine alternative platforms that would allow us to exchange more diverse kinds of knowledge. In the following, I once more revisit the themes running through this dissertation, this time considering the role of infrastructure, community-building, science education and craft knowledge in participatory research today and in the future, while taking inspiration from previous chapters.

[68] For example, *Letters 1916-1923* built their own project website, and organised on-site talks and workshops across Ireland, see http://letters1916.maynoothuniversity.ie/. Accessed on 11 August 2022.
[69] Sally Shuttleworth, "Life in the Zooniverse: Working with Citizen Science," *Journal of Literature and Science* 10, no. 1 (2017): 48.

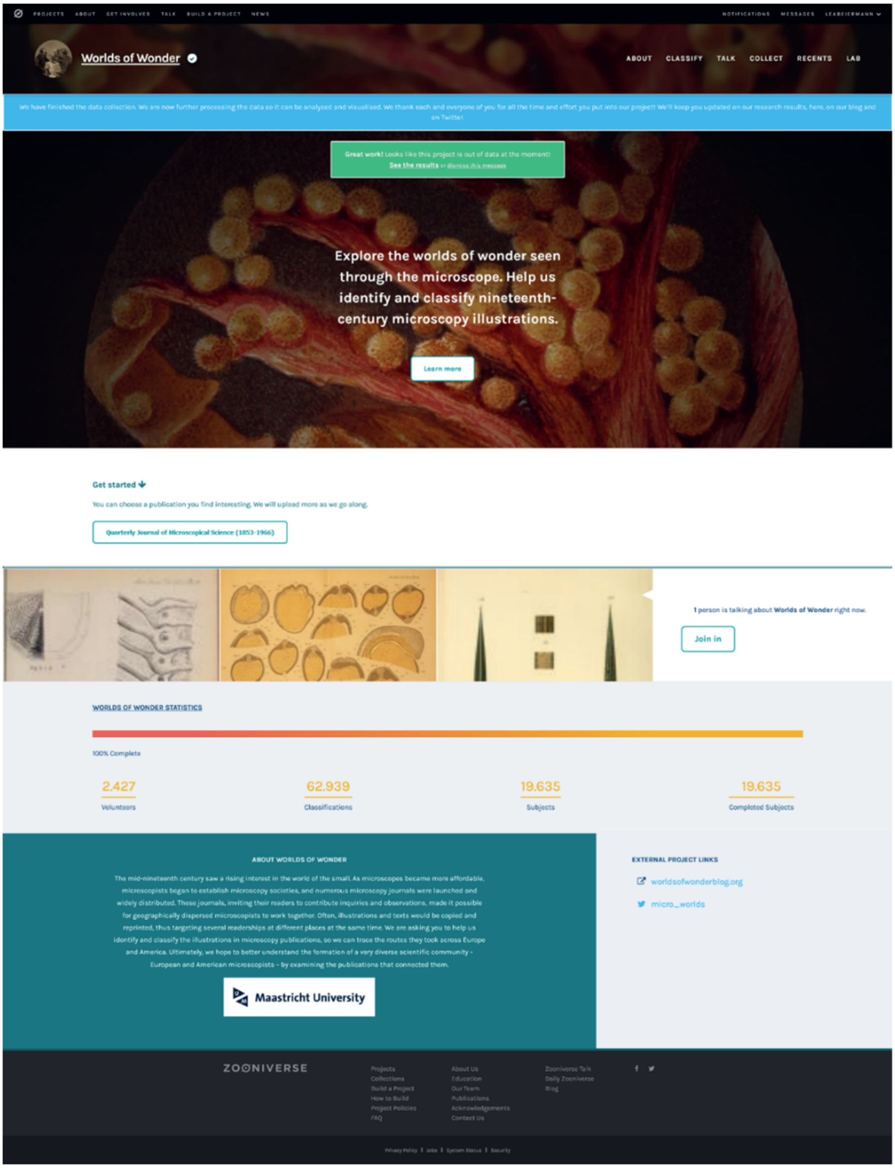

Figure 5.2 *Worlds of Wonder* project landing page, including project statistics and description. Screenshot.

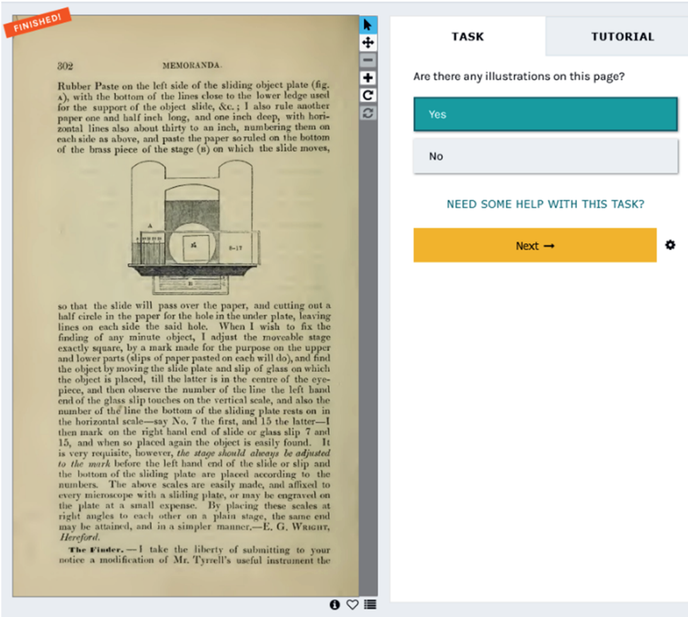

Figure 5.3 Identifying illustrations in the project workflow. Screenshot.

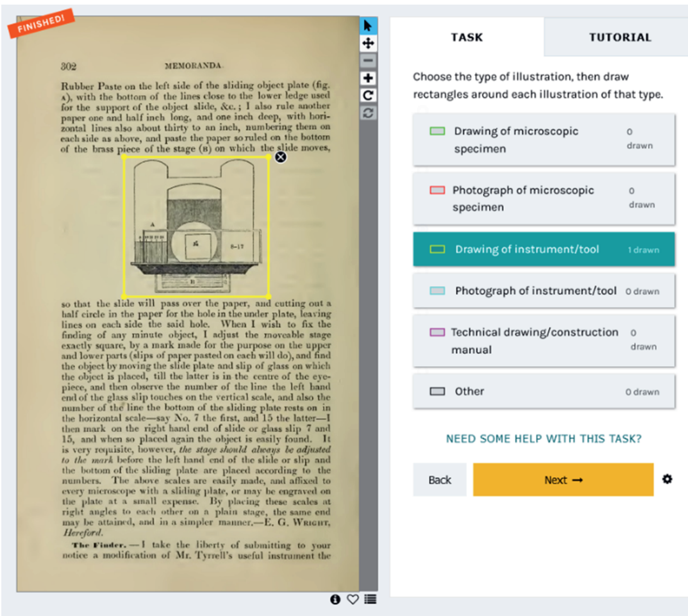

Figure 5.4 Classifying illustrations in the project workflow. Screenshot.

Infrastructure

The Zooniverse, which hosted the *Worlds of Wonder* project, has become one of the biggest platforms for citizen science. On its main page, the website guides visitors to a list of all projects hosted and supported by the Zooniverse, and explains the objectives underlying the platform, portraying citizen science as an opportunity for collaboration between citizen scientists and professional researchers. On its subpages, the Zooniverse gives visitors access to its blog and the "Talk" chat forum – where citizen scientists and project organisers can discuss general questions concerning the platform – as well as the project builder. With the help of the project builder, the Zooniverse provides organisers of citizen science projects with project-specific digital infrastructure, including a project landing page that can be populated with information about the project and its organisers, a customisable workflow and access to the collected data as CSV files, as well as a chat forum where participants and organisers can discuss project-related issues.

In the case of *Worlds of Wonder*, the landing page offered some general information about the history of microscopy, the project organisers (myself, my PhD advisors, and the MUSTS research group at Maastricht University), and it described the goal of *Worlds of Wonder*: tracing the circulation of nineteenth-century microscopy illustrations and learning more about scientific illustrators (Fig. 5.2). The chat forum that accompanied the project provided a digital space to discuss individual historical illustrations and illustrators, flag problems in the workflow, and share educational resources dealing with the history of microscopy. In the *Worlds of Wonder* workflow, citizen scientists were shown a page from a nineteenth-century microscopy publication and asked to identify illustrations on that page, describe their content and transcribe the signature of the illustrator if possible. Each page was shown to at least five citizen scientists if the first classifiers said it included an illustration, or to at least three if the classifiers agreed that there was no illustration (Fig. 5.3 and 5.4). After completing these tasks, the citizen scientists could choose to discuss the page they had classified in the *Worlds of Wonder* chat forum.[70]

Usually, the workflow of a Zooniverse project is set up by the project organisers before the start of the project, drawing on a range of common tasks made available by the Zooniverse (e.g. transcribing text or tagging images). Most Zooniverse projects are therefore an example of what is called "invited participation" in the citizen science scholarship.[71] Citizen scientists are asked by the project organisers, most often researchers working at universities, research institutes and GLAM institutions, to contribute to the project, and they tend to

[70] See Appendix C for a more detailed overview of the workflow.
[71] See Mahr and Dickel, "Citizen Science Beyond Invited Participation."

have little power over the project design.[72] Moreover, Zooniverse workflows typically ask citizen scientists to enter machine-readable data, including numbers, answers to yes-or-no questions, and transcriptions of text, which limits the kinds of knowledge that can be generated in a project workflow, leaving little room for nuanced historical interpretation and critical analysis.[73]

In exploring more democratic alternative models to invited participation, the sociologists Dana Mahr and Sascha Dickel have made a case for "self-governed infrastructures," i.e. infrastructures which are governed by the citizen scientists instead of the project leaders and would facilitate an exchange of more diverse kinds of knowledge.[74] While Mahr and Dickel's idea of self-governed infrastructures is compelling, it seems difficult to implement in web-based crowdsourcing projects whose central aim is to generate a large amount of machine-readable data. These projects tend to follow the FAIR principles for data exchange, which ask for findable, accessible, interoperable and reusable data. The demands set by the FAIR agenda for data reuse can only be met with highly standardised and machine-readable data.[75] To give a case in point, the workflow designed for *Worlds of Wonder* was based on the workflow of *Science Gossip*, an earlier Zooniverse project on nineteenth-century scientific illustrators. As a result, the data generated in *Worlds of Wonder* could be combined and compared with the *Science Gossip* dataset easily. This shows that citizen science infrastructures are not only determined by the project organisers, or the Zooniverse platform, but also constrained by principles of data reuse, which limits the extent to which they can be designed and governed by citizen scientists.

Mahr and Dickel's call for self-governed infrastructures is difficult to reconcile with the high degree of standardisation required by crowdsourcing projects that seek to answer research questions with the help of big data. Ultimately, as Mahr and Dickel's paper implies, the consequence would be to abolish crowdsourced citizen science altogether.[76] But that would mean abandoning research questions that can only be answered with the help of crowdsourcing – and failing to acknowledge that many volunteers do find a lot of joy in crowdsourced citizen science. Instead, I would argue that there are ways of tweaking the digital infrastructures of citizen science platforms to accommodate

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[72] See Mirowski, "Against Citizen Science." GLAM is an acronym for galleries, libraries, archives and museums.
[73] The chat forum, however, provides some room for critical discussion in Zooniverse projects.
[74] See Mahr and Dickel, "Citizen Science Beyond Invited Participation." See also Mahr, *Citizen Science: Partizipative Wissenschaft im späten 19. und frühen 20. Jahrhundert*.
[75] See Jamie Williams et al., "Maximising the Impact and Reuse of Citizen Science Data," in *Citizen Science: Innovation in Open Science, Society and Policy* ed. Susanne Hecker et al. (London: UCL Press, 2018): 321-336.
[76] Mahr and Dickel seem to side with the biohackers they quote in their paper, who "reject the crowdsourcing approach to citizen science, because it would keep them in a heteronomous position." Mahr and Dickel, "Citizen Science Beyond Invited Participation," 40.

more diverse kinds of knowledge in a project than the data generated in the workflow.

To that end, this chapter revisits Janet Vertesi's concept of infrastructural "seams" and "seamfulness" discussed in the last chapter, and researchers' capacity to align and work across different infrastructures.[77] The previous chapter has examined Abbe's skill in working across infrastructures, often with the help of "infrastructural allies" in the RMS.[78] In *Worlds of Wonder*, too, citizen scientists had to work across infrastructures. The publications uploaded to the Zooniverse were originally hosted by the Biodiversity Heritage Library (BHL), and a link connected the image in the Zooniverse workflow with the original file in the BHL. The citizen scientists were encouraged to consult the BHL file when the resolution of the image in the workflow was not high enough, or when the image file was corrupted in some way and not accessible. In the project chat, discussions ensued about how to align the two platforms – BHL and the Zooniverse – and work across different browser tabs. More experienced citizen scientists often served as infrastructural allies, explaining what they considered a good approach to less experienced volunteers. Over time, the *Worlds of Wonder* participants even began to look for different uploaded files and editions in the BHL to better determine the names of illustrators, and they searched for sources that would provide some biographical information on those illustrators. Working across different platforms thus made it possible for citizen scientists to follow their own research interests to some extent and put the single page shown to them in the workflow into (historical) context.

Matthew Chalmers et al. argue that "seamfulness" can be a conscious design decision in developing digital infrastructures, where different (online and on-site) infrastructures are connected but not seamlessly aligned: "designers take advantage of the physical gaps, limits and similar characteristics that constitute a design medium – rather than smoothing them out or ignoring them."[79] Reviewing a game where players have to collect virtual "coins" from outside a wireless network and bring them back inside the network, Chalmers et al. observe that "[infrastructure] becomes a central feature of the game, rather than the peripheral technical context" and "[the] deliberate exposing of selected aspects of the infrastructure suggests something of how users could develop their own ways to take advantage of the limits, gaps and seams in technology."[80] Applying Chalmers et al.'s concept of "seamfulness by design" to citizen science means that by developing "seamful" crowdsourcing projects we can link heterogeneous

[77] See Vertesi, "Seamful Spaces."
[78] Beaulieu, "From Co-Location to Co-Presence," 461.
[79] Matthew Chalmers et al., "Gaming on the Edge: Using Seams in Ubicomp Games," *Proceedings of the 2005 ACM SIGCHI International Conference on Advances in Computer Entertainment Technology* (2005): 306. Chalmers's work is also discussed in Vertesi, "Seamful Spaces."
[80] See Chalmers et al., "Gaming on the Edge."

infrastructures and better accommodate diverse kinds of knowledge, without compromising on the quality of machine-readable data generated in the workflow. While the working-across-platforms happened rather accidentally in *Worlds of Wonder*, it could be a design feature of future projects, encouraging citizen scientists to work across multiple online (and on-site) infrastructures. A citizen science platform like the Zooniverse would then become a digital space where infrastructures can be aligned – through links, discussion, and with the help of infrastructural allies – and where diverse kinds of knowledge can be brought into conversation, enriching both the research project and the work process of citizen scientists.

Community-Building

Although the collection of a large amount of high-quality data is at the heart of crowdsourced citizen science projects, this is not their sole purpose. With the move away from volunteer computing towards more participatory citizen science projects came a shift towards community-building and science education. Especially in projects established by GLAM organisations and in citizen humanities initiatives, building a community of volunteers who are eager to engage with archival and other materials – and potentially visit the GLAM host institution – has become an end in itself. As the curator Trevor Owens writes, "[if] the goal is to get people to engage with collections and with the past, then the [crowdsourced] transcripts are actually a wonderful by-product of offering meaningful activities for the public to engage in."[81]

The Zooniverse promotes its community of citizen scientists – the "Zooites," as it were – on its main page, presenting the community as a central element of every Zooniverse project. The Zooniverse promises that citizen scientists will get to know professional researchers through a crowdsourcing project, while project organisers will find a crowd of volunteers to help with their data analysis in return. According to Joe Cox et al., there seems to be a correlation between project organisers' ability to foster a community of dedicated citizen scientists and the project's scientific output, giving the Zooniverse another reason to promote its community-building capacity.[82] Much like the late-nineteenth-century communities of microscopists studied in the previous chapters, web-based citizen science communities are virtual, being constituted of an international crowd of volunteers. Zooites tend to meet in the general chat forum of the Zooniverse and the project-specific chat forum, but their discussions extend

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[81] Trevor Owens, "Making Crowdsourcing Compatible with the Missions and Values of Cultural Heritage Organisations," in *Crowdsourcing Our Cultural Heritage*, ed. Mia Ridge (Ashgate: Aldershot, 2014), 278.

[82] See Cox et al., "Defining and Measuring Success in Online Citizen Science."

beyond the Zooniverse into the virtual spaces connected to a project, in the case of *Worlds of Wonder* a blog and Twitter account. Considering what we have learned about late-nineteenth-century microscopy in previous chapters, there seem to be two aspects worth keeping in mind when we set out to build communities in present-day citizen science: one is the possibility of technological innovation through collaborative work and thinking of citizen scientists as innovative users, and the other is the need to gain a better sense of how a citizen science community develops over time.

In their analysis of the SETI@home user community, Élise Tancoigne and Jérôme Baudry write that the SETI@home volunteers were "less likely to have stars in their eyes than a screwdriver in hand."[83] The volunteers were connected not so much by a common interest in astronomy and the citizen science project itself but by their shared passion for the machines it ran on, their personal computers. Tancoigne and Baudry conclude that "the world of online citizen science could be enriched by focusing less on participation or science and more on the technology itself, asking not 'who is taking part?' or 'how is knowledge being produced?' but rather, 'what is the apparatus sustaining this project?'."[84] Indeed, the citizen science scholarship has been concerned with questions of data collection and scientific authority, but much less attention has been paid to citizen scientists' use of technology. Drawing on the previous chapter, which looked at the Fellows of the RMS through the lens of user innovation, we can extend Tancoigne and Baudry's argument and ask what we might gain by conceiving of citizen scientists as a user innovation community.

Especially if we want to develop more seamful infrastructures in citizen science, it may be rewarding to conceive of citizen scientists as a community of innovative users. When citizen scientists work across the seams of different infrastructures, they engage in a "lay practice of heterogeneous engineering," to use Vertesi's term: a practice that produces a "fleeting alignment or misalignment of infrastructures to accomplish local, mundane tasks."[85] This applies to *Worlds of Wonder*, where participants worked across the Zooniverse and BHL platforms, but probably even more so to projects in which citizen scientists collect data themselves, e.g. by counting animals in their local area or measuring rainfall. For example, in the first citizen science project initiated by the members of the Quekett Microscopical Club, mapping the spread of an invasive drosophila species, participants built their own traps to catch the flies. Thinking of a project's citizen

[83] Tancoigne and Baudry, "La tête dans les étoiles?," 16.
[84] Tancoigne and Baudry, "La tête dans les étoiles?," 17.
[85] Vertesi, "Seamful Spaces," 269. See also John Law, "Technology and Heterogeneous Engineering: The Case of Portuguese Expansion," in *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*, anniversary ed., ed. Wiebe E. Bijker, Thomas Parke Hughes, and Trevor Pinch (Cambridge, Mass.: MIT Press, 2012), 105-128.

scientists as a community of innovative users can help us be more aware of (and facilitate) collaborative innovation of technologies in participatory research.

The history of innovating microscope users also reminds us that heterogeneous scientific communities are volatile and likely to change over time. The citizen science literature has come to acknowledge community-building as an important feature of citizen science, but it tends to conceive of citizen science communities as rather static, only looking at snapshots of the community at the peak of participation (or sometimes, in the recruiting phase).[86] However, in order to build more long-term alliances between trained and untrained researchers, it is essential to understand how a community of citizen scientists develops over time. A complaint commonly made by citizen scientists is that project organisers tend to abandon the community after the data collection is over.[87] By researching community-building (and unbuilding) before, during and after data collection, we might be able to design citizen science platforms that encourage interaction among participants at every stage of the project and help project organisers and citizen scientists to develop more sustainable relationships.

Science Education and Craft Knowledge

Citizen science came with the promise of making science more accessible by involving volunteers in scientific research and increasing their "scientific literacy."[88] Citizen science has therefore been a project of science education from the beginning, fuelling the hope that it might help restore trust in science by educating participants on scientific methods. Bruno Strasser et al. write that project organisers have always emphasised the notion of citizen science as informal science education: "By involving students, as well as adults, in authentic research projects, rather than 'school science', organizers of 'citizen science' projects could claim that participation would increase understanding of the research process, thereby aligning themselves with educational policies."[89]

Whether citizen science has kept its promise of making participants more scientifically literate remains debated, with some scholars seeing little evidence of citizen scientists engaging with research on a more profound level than ticking

[86] See, for example, Miyoko Chu, Patricia Leonard, and Flisa Stevenson, "Growing the Base for Citizen Science: Recruiting and Engaging Participants," in *Citizen Science: Public Participation in Environmental Research*, ed. L. Dickinson Janis and Richard E. Bonney, Jr. (Ithaca: Comstock Publishing Associates, 2012), 69-81.
[87] Peter Mason, the software engineer who helped to analyse the *Worlds of Wonder* data, only agreed to collaborate on the condition that the project organisers would not disappear at the end of the project, which he had experienced many times before.
[88] Bruno J. Strasser et al., "'Citizen Science'? Rethinking Science and Public Participation," *Science & Technology Studies* 32, no. 2 (2019): 62.
[89] Strasser et al., "'Citizen Science'? Rethinking Science and Public Participation," 64.

boxes in the project workflow and perhaps gaining some factual knowledge.[90] Others, however, have found that web-based citizen science can help participants gain a new perspective on scientific research, including a better understanding of the process of peer review, or how failure can be beneficial to knowledge production.[91] In *Worlds of Wonder*, many participants did not do more than what was asked of them in the workflow, identifying illustrations and illustrators on the pages shown, but a few discussed how to find additional historical sources online in order to determine the names of illustrators, for instance with the help of biographical notes and obituaries, or how to find different scans of publications in which the signature of an illustrator was easier to decipher. In that sense, there is some evidence that participants' literacy of digital historical archives increased as they learned to find useful sources online, which in turn enriched not only discussions in the *Worlds of Wonder* chat forum, but also this dissertation.

Looking back on the science education promoted by microscopists in the previous chapters, we find that today's professed goal of education through citizen science in some ways echoes the hopes of late-nineteenth-century popularisers of science. As Mahr writes, the *fin de siècle* saw a coming together of ideals of scientific participation and popularisation which led the German scientific writer Wilhelm Bölsche to declare an age of "community research."[92] The microscopists in this dissertation were similarly eager to involve the public in microscopy as both a scientific and leisure pursuit and integrate microscopy in school and university education. Since microscopists did not primarily exchange quantitative data but qualitative observations of microscope specimens, as well as craft knowledge of microscopy, they had to conceive of ways of communicating knowledge that was difficult to put into writing. It is therefore worthwhile to turn to late-nineteenth-century microscopy to reimagine today's citizen science projects as sites of learning and education in the sciences and humanities. Even though citizen science has been bound up with science education from its inception, it often continues to be geared towards data collection, with science education only being an afterthought in the project design. Taking inspiration from the history of microscopy may help to change that.[93]

The previous chapters have shown that paper tools such as working images were important for microscopists to acquire a diverse set of skills, including how to observe microscope specimens and how to mount microscope slides. In fact, working images were so bound up with the process of learning how to observe

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[90] Some empirical research into the learning effects of citizen science is discussed in Strasser et al., "'Citizen Science'? Rethinking Science and Public Participation."
[91] See Maria Aristeidou and Christothea Herodotou, "Online Citizen Science: A Systematic Review of Effects on Learning and Scientific Literacy," *Citizen Science: Theory and Practice* 5, no. 1 (2020): 1-12.
[92] Mahr, *Citizen Science: Partizipative Wissenschaft im späten 19. und frühen 20. Jahrhundert*, 22.
[93] See Maria Aristeidou, Eileen Scanlon, and Mike Sharples, "Science Learning in Online Communities of Scientific Investigations: Evidence and Suggestions" (American Educational Research Association Annual Conference, San Antonio, TX, 2017).

specimens that often the image itself became the object of investigation, with microscopists observing and copying images just as carefully as they examined a specimen under the microscope. This is in line with Lorraine Daston's argument that "taking notes entails taking note."[94] Daston emphasises that note-taking is integral not only to the observational practices of natural scientists but also to research undertaken in the humanities, where scholars enter a (virtual) dialogue with other writers by annotating their work.[95] Taking note(s) in the margins of a text means following and reproducing another scholar's train of thought, thinking and learning along with them.

Applying these insights to citizen science means that we may be able to better support citizen scientists in their learning by facilitating note-taking and sketching practices in the project workflow. Images are among the most common materials analysed in citizen science projects.[96] Thinking of the images that citizen scientists interact with as digital paper tools can help us conceive of more diverse forms of interaction than workflow tasks usually allow for, like tagging, classifying or transcribing images. Citizen science platforms could easily make it possible to annotate material – not with the goal of producing machine-readable data but solely with a view to supporting citizen scientists in taking note(s). As Mary Flanagan and Peter Carini have shown, some citizen scientists annotate material already, even if the project workflow does not ask them to.[97] In the *Metadata Games* software studied by the two authors, one citizen scientist appropriated the tagging task – which asks participants to add metadata to images so they can be found more easily by others – to add "inquiry phrases, such as 'want to know more about this culture'."[98] In recent years, digital humanists have developed a wealth of digital tools that support the individual and collaborative annotation of sources, such as MIT's *Annotation Studio*, *Mediate,* an annotation tool for audio-visual media developed by the University of Rochester, or *Manifold* of the University of Minnesota Press and the CUNY Graduate Center, to name just a few. Making tools that facilitate rich annotation available on citizen science platforms as part of the project workflow would help to make participants' learning experience a much more central element of citizen science.

Finally, the previous chapters have shown that subgroups of the microscopy community sometimes organised physical meetings alongside their virtual exchanges. Reproducing Abbe's experiments in different places made on-site tinkering with microscopes possible, inspiring the RMS Fellows to use those

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[94] Daston, "Taking Note(s)," 445.
[95] See Daston, "Taking Note(s)."
[96] See Mia Ridge, "From Tagging to Theorizing: Deepening Engagement with Cultural Heritage through Crowdsourcing," *Curator: The Museum Journal* 56, no. 4 (2013): 435-450.
[97] See Mary Flanagan and Peter Carini, "How Games Can Help Us Access and Understand Archival Images," *American Archivist* 75, no. 2 (2012): 514-537.
[98] Flanagan and Carini, "Games," 533.

instruments differently than intended or think of new devices altogether. Complementing the virtual correspondence between Abbe and the Fellows with physical meetings helped to foster the exchange of craft knowledge, as did the local subgroups and meetings organised by the British Postal Microscopical Society. Judging from my experience in running *Worlds of Wonder*, present-day digital citizen science projects seem to have a similar way of spilling into the world beyond the screen. For example, coming across the *Worlds of Wonder* website encouraged a private Dutch collector of historical microscopy paraphernalia to reach out to the project organisers and examine his collection of microscopy publications together. *Worlds of Wonder* also inspired one of the citizen scientists – the software engineer who helped with the data analysis – to take up microscopy during the Covid-19 lockdowns. Moreover, I showed slides of microscopic animals with a magic lantern – a historical slide projector – during a public lecture I gave and helped members of the audience operate the magic lantern afterwards.[99] Encouraging such spillovers of web-based citizen science into real-life encounters can help both trained and untrained researchers in citizen science projects develop skills that complement the knowledge generated online.

Conclusion

In order to explain how late-nineteenth-century microscopists learned their craft together despite being scattered across space, this chapter has drawn together the thematic threads that ran through the previous chapters. It has demonstrated that microscopists attuned their knowledge infrastructures to sharing skills in microscopy, formed (virtual) communities around those infrastructures of making and doing microscopy, and provided a scientific education that reached diverse groups of practitioners, even those studying microscopy outside formal spaces of learning. As explained in the methodology section, this dissertation followed Shove, Trentmann and Watson's practice-oriented definition of infrastructures as material arrangements integral to their users' practices.[100] More specifically, it explored the role of infrastructure in sharing highly skilled scientific practices, which late-nineteenth-century microscopists (and present-day historians) often deemed particularly difficult to learn without direct on-site collaboration. This dissertation, therefore, has asked us to (re)consider the role of infrastructure in

[99] This was inspired by a public lecture I helped to organise with the ConSciCom research group in 2016. See "Science and the Victorian Public: A Magic Lantern Performance," *Constructing Scientific Communities*, https://conscicom.web.ox.ac.uk/article/science-and-the-victorian-public-a-magic-lantern-performance. Accessed on 22 June 2022.
[100] See Shove, Trentmann, and Watson, "Introduction – Infrastructures in Practice: The Evolution of Demand in Networked Societies." See also Shove, "Matters of Practice."

acquiring skills in microscopy, inviting further research into the kinds of infrastructure that may help generate craft knowledge at a distance.

As outlined in the introduction, the history of microscopy in the late nineteenth century has not been a favourite topic for historians of science, who have tended to focus on how microscope users established that what they saw through the microscope was true, at a time when the use of the instrument for scientific research was still controversial. This dissertation, however, has shown that the late nineteenth century is a crucial period if we want to understand how infrastructures of making and doing microscopy were built, and how they helped to share craft knowledge of microscopy widely. The second half of the nineteenth century saw the rise of microscopy societies, publications, and commercial slide and instrument makers, aiming to teach their members, readers and clients skills in microscopy. This flurry of activity around microscopy lasted only a couple of decades. It peaked in the 1870s and early 1880s, but was almost gone by the turn of the twentieth century. Yet microscopists left a lasting mark on the American postal law, helped the advent of industrial science by collaborating with Abbe and the Zeiss company, and made microscopy accessible to a whole generation of students inside and outside educational institutions when training in microscopy had only begun to make its way into school and university curricula.

In this final chapter we have found that the history of microscopy in the late nineteenth century does not provide us with a blueprint of how to organise citizen science projects today, and assuming so would be anachronistic. However, the history of microscopy can serve as a "heuristic tool" that makes us more sensitive to the possibilities and limitations of organised forms of knowledge exchange among a diverse group of geographically dispersed researchers.[101] As Shuttleworth and Charnley put it, "[if] the story of today's science communication is – as is often claimed – one of new technologies facilitating new platforms and new types of communication, this is in fact a very old story."[102] Instead of suggesting direct parallels between nineteenth-century and twenty-first-century forms of participation in scientific research, this chapter has revisited some of the theoretical concepts that informed previous chapters, this time with a view to developing future models of citizen science.

The chapter has argued that designing "seamful" digital infrastructure for citizen science projects may allow us to exchange more diverse kinds of knowledge than the quantitative data collected in the Zooniverse workflow. Seamfulness can also help us solve the tension between big data citizen science relying on highly standardised infrastructure and giving citizen scientists more power over infrastructure design. Citizen scientists who are "infrastructural allies" have learned to work across infrastructures and can teach other volunteers ways of

[101] Shuttleworth, "Life in the Zooniverse," 48.
[102] Shuttleworth and Charnley, "Science Periodicals in the Nineteenth and Twenty-First Centuries," 2.

"heterogeneous engineering." Moreover, harking back to the user innovation literature, we have learned that it may be rewarding to think of citizen scientists as a community of innovative users of technologies, a community which is not static but changes over the course of a research project. Keeping in mind the importance of paper tools for learning microscopy in the late nineteenth century, the chapter has also suggested to think of the images citizen scientists analyse as digital paper tools and facilitate deeper engagement with them, for instance with the help of rich annotation.

We are becoming more and more accustomed to working and learning together remotely, a development spurred by the rise of interactive digital platforms like the Zooniverse, but also, in 2020, by the outbreak of the Covid-19 pandemic. The history of microscopy in the late nineteenth century challenges us to think better about what kinds of knowledge we can share at a distance, and the kinds of infrastructures we need to do so. In 1866, James Glaisher, then president of the Microscopical Society of London, declared that to advance microscopy a "co-operation of observers scattered all over the world is necessary, and these should include all classes, for so universal are the objects scattered which we wish to study, that a large co-operation is indispensable."[103] Glaisher's grand vision of a "large co-operation" of scientific observers with diverse backgrounds and skills lost momentum as the microscopy community declined around 1900. And yet, as this dissertation proves, the history of microscopy continues to inspire us to imagine and realise collaborations among "observers scattered all over the world."

[103] Glaisher, "President's Address," 48.

Appendix A: Archives Visited

England

Museum of the History of Science, Oxford
 MSS Royal Microscopical Society
 RMS Internal Archives

Germany

Zeiss company archive, Jena

United States

Academy of Natural Sciences, Philadelphia
 Papers of the American Postal Micro-cabinet Club
National Museum of American History Library, Washington, DC
 Trade Literature Collection

Digital Archives

Biodiversity Heritage Library, https://www.biodiversitylibrary.org/
HathiTrust, https://www.hathitrust.org/
Internet Archive, https://archive.org/

Appendix B: *Worlds of Wonder* Publications Classified

Books

Bausch, Edward. *Manipulation of the Microscope*. Rochester, NY: Bausch & Lomb Optical Company, 1891.

Beale, Lionel S. *How to Work with the Microscope. A Course of Lectures on the Practical Use of the Instrument and Microscopical Manipulation*. London: John Churchill, 1861.

Brocklesby, John. *Views of the Microscopic World*. New York: Pratt, Woodford & Company, 1851.

Carpenter, William B. *The Microscope and Its Revelations*. London: John Churchill, 1856.

Catlow, Agnes. *Drops of Water. Their Marvelous and Beautiful Inhabitants Displayed by the Microscope*. London: Reeve and Benham, 1851.

Cooke, Mordecai C. *One Thousand Objects for the Microscope*. London and New York: Frederick Warne and Co., 1869.

Cooke, Mordecai C. *Rust, Smut, Mildew, & Mould. An Introduction to the Study of Microscopic Fungi*. 4th ed. London: Hardwicke and Bogue, 1878.

Gosse, Philip Henry. *Evenings at the Microscope; or Researches among the Minuter Organs and Forms of Animal Life*. New York: P. F. Collier & Son, 1860(?).

Griffith, John W. *An Elementary Text-Book of the Microscope*. London: John van Voorst, 1864.

Griffith, John, and Arthur Henfrey. *The Micrographic Dictionary*. 2 vols. 3rd ed. London: John van Voorst, 1875.

Hogg, Jabez. *The Microscope: Its History, Construction, and Applications*. London: The Illustrated London Library and W. S. Orr and Co., 1854.

Pritchard, Andrew. *Microscopic Illustrations of Living Objects*. Rev ed. London: Whittaker and Co., 1840.

Quekett, John. *A Practical Treatise on the Use of the Microscope, Including the Different Methods of Preparing and Examining Animal, Vegetable, and Mineral Structures*. London: Hippolyte Baillière, 1848.

Slack, Henry J. *Marvels of Pond-Life. Or, a Year's Microscopic Recreations Among the Polyps, Infusoria, Rotifers, Water-Bears, and Polyzoa*. London: Groombridge and Sons, 1861.

Smith, J. Edwards. *How to See with the Microscope*. 2nd ed. Chicago: Duncan Brothers, 1885.

Somerville, Mary. *On Molecular and Microscopic Science*. 2 vols. London: John Murray, 1869.

Ward, Mary. *Microscope Teachings: Descriptions of Various Objects of Especial Interest and Beauty Adapted for Microscopic Observation*. London: Groombridge and Sons, 1866.
Wythes, Joseph H. *The Microscopist*. 2nd ed. Philadelphia: Lindsay and Blakiston, 1853.

Periodicals

Hints on the Preservation of Living Objects and Their Examination Under the Microscope (1879-1882), GB. Volumes classified: 1879-1882.
Journal of Applied Microscopy (1898-1903), US. Volumes classified: 1898-1899.
Quarterly Journal of Microscopical Science (1853-1966), GB. Volumes classified: 1853-1888.
The American Monthly Microscopical Journal (1880-1902), US. Volumes classified: 1880-1888, 1890-1891, 1893-1902.
The Microscopical News and Northern Microscopist (1881-1884), GB. Volumes classified: 1881, 1883-1884.
Zeitschrift für wissenschaftliche Mikroskopie und für mikroskopische Technik (1884-1970), GER. Volumes classified: 1884-1891.

The data collected through *Worlds of Wonder*, as well as the Python scripts used to analyse them, can be found on DataverseNL:

Beiermann, Lea, 2021, "'Advancing Microscopy': New Media and Citizen Microscopists in Nineteenth-Century Britain and America," https://doi.org/10.34894/LRBQF5, DataverseNL, V2.

Appendix C: *Worlds of Wonder* Project Workflow

The *Worlds of Wonder* classification workflow consisted of four tasks. The citizen scientists were shown a page from a nineteenth-century microscopy publication and asked:

1. Are there any illustrations on this page?
    a. Yes/No

2. Choose the type of illustration, then draw rectangles around each illustration of that type.
    a. Drawing of microscopic specimen
    b. Photograph of microscopic specimen
    c. Drawing of instrument/tool
    d. Photograph of instrument/tool
    e. Technical drawing/construction manual
    f. Other

3. Mark any handwritten captions and contributors in the illustration(s). Also mark any names of manufacturers of technical equipment.
    a. Caption
    b. Contributor
    c. Manufacturer

4. Add keywords to describe the illustration(s). Separate each term with a comma.

List of Figures

for the Advancement of Science, Literature and Art, https://devonassoc.org.uk/the-hudson-transparencies/.

Figure 2.11 Example of one of Hudson's transparencies in room lighting (left) and backlit (right). Note that this transparency does not show rotifers but other microorganisms (*Amoeba princeps, Actinophrys sol*, and *Raphidiophrys viridis*). Image courtesy of Robin Wootton. The image was first published in Wootton, R. (2011). The Hudson Transparencies. A Set of Remarkable Visual Aids by a Distinguished Victorian Microscopist. *Report and Transactions of the Devonshire Association for the Advancement of Science, Literature and Art*, 143, 61-90.

Figure 2.12 Philip Henry Gosse's illustration of the crown animalcule (a and b) and other builder animalcules in the *Popular Science Review* (1862), 1, Plate XXVI. Image from the Biodiversity Heritage Library. Contributed by the Natural History Museum Library, London.

Figure 2.13 H. E. Forrest's illustration of a crown animalcule in Thomas Bolton's flyleaves, 1880. Bolton, T. (1879-1882). *Hints on the Preservation of Living Objects and Their Examination Under the Microscope*. Birmingham: Herald Printing Offices. Image from the Biodiversity Heritage Library. Contributed by the University of Toronto Thomas Fisher Rare Book Library.

Figure 2.14 One of Thomas Bolton's handwritten descriptions, duplicated through autographic printing, 1880. Bolton, T. (1879-1882). *Hints on the Preservation of Living Objects and Their Examination Under the Microscope*. Birmingham: Herald Printing Offices. Image from the Biodiversity Heritage Library. Contributed by the University of Toronto Thomas Fisher Rare Book Library.

Figure 2.15 People, books and journals frequently mentioned in Bolton's flyleaves (1879–1882), sized and coloured according to their frequency of occurrence. The word cloud shows Bolton's close connection to *The Midland Naturalist*, as well as Gosse and Hudson.

Figure 3.1 Map of British microscopy societies and natural history societies with a strong link to microscopy, established between 1860 and 1900. Only a few of those societies survived until (or after) the end of the century. Map data: Google, INEGI.

Figure 3.2 Map of microscopy societies in the United States that existed between 1876 and 1893, according to two lists of societies published in these years. In

Figure 5.3 Identifying illustrations in the project workflow. Screenshot.

Figure 5.4 Classifying illustrations in the project workflow. Screenshot.

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Academic Impact

This dissertation started from the premise that working with a microscope required a kind of craft knowledge that was difficult to teach and learn without personal instruction. Late-nineteenth-century microscopists themselves observed that the use of the microscope in making observations, the production of microscopes, as well as the making of slides and other accessories required knowledge that could not always be found in books. Microscopy asked for a steady hand and care in handling microscopes and microscopic objects, skill in working with varying mounting ingredients in different climatic conditions, as well as the ability to interpret what was seen through the microscope. For a long time, historians of science tended to argue that acquiring such skills depended on on-site interaction among artisans, but a few scholars have begun to explore alternative ways of craft knowledge exchange in the early modern age and beyond (see Chapter One). This dissertation contributes to that literature by showing that microscopists' long-distance exchange of craft knowledge was intimately linked to the emergence of new trade and communication infrastructures in the second half of the nineteenth century, which afforded the sharing of skills.

As explained in the introduction, the history of microscopy, and especially microscopy in the late nineteenth century, has not been a favourite topic for historians of science. The literature has so far primarily looked at how microscope users came to agree that what they saw through the microscope was true, most often focusing on the time between the late seventeenth to the early nineteenth century, when the use of the microscope for scientific research was still controversial. This dissertation, however, has shown that the late nineteenth century is a crucial period if we want to understand how infrastructures of making and doing microscopy were built, and how they helped to share craft knowledge of microscopy widely. The second half of the nineteenth century saw the rise of microscopy societies, publications, and commercial slide and instrument makers, aiming to teach their members, readers, and customers, skills in microscopy. This flurry of activity around microscopy lasted only a couple of decades. It peaked in the 1870s and early 1880s, but was almost gone by the turn of the twentieth century. Yet, as this dissertation has shown, microscopists left a lasting mark on the American postal law, helped the advent of industrial science, and made microscopy accessible to a whole generation of students when training in microscopy had only begun to make its way into school and university curricula.

Microscopists attuned their knowledge infrastructures to sharing skills in microscopy and vice versa, for instance by developing mounting media that would withstand the strain of postal exchange. They formed (virtual) communities around their knowledge infrastructures and provided a scientific education that reached diverse groups of learners, even those studying microscopy outside formal spaces of learning. This dissertation, therefore, asks us to consider the role of infrastructure in acquiring skills in microscopy and beyond, inviting further research into the kinds of infrastructure that allow for the sharing and generation of craft knowledge at a distance. Moreover, as I have argued in Chapter Five, the history of microscopy can serve as a heuristic tool that directs our attention to the long historical trajectory of collaborations between formally trained and untrained researchers, and the challenges these collaborations entail, which can help us reimagine present-day and future participatory science projects, like web-based citizen science initiatives.

During the PhD, I noticed that my research speaks to scholars working in many different fields, including historians of science and technology, media studies scholars, STS researchers with an interest in infrastructure studies, digital humanists, data scientists, and even life scientists who work with microscopes in their labs on a day-to-day basis. I have been fortunate to meet and learn from these diverse scholars at national and international workshops and conferences, and through several publications, some of them written collaboratively. Over the course of the PhD, I presented my research at 12 (inter)national workshops and conferences and gave one invited lecture at the University of Heidelberg. I also presented my work at numerous events at Maastricht University, including departmental and graduate school meetings, a crowdsourcing workshop at the UM Institute of Data Science, and a conference to celebrate the launch of the BA Digital Society.

I published a peer-reviewed paper in *The British Journal for the History of Science* (BJHS), an earlier version of which received the 2020 Singer Prize of the British Society for the History of Science (BSHS). Moreover, I turned Chapter Four into a feature article for *Physics Today*, which is currently being edited. Another paper (based on Chapter Two) will be published as a chapter in *Networks: The Creation and Circulation of Knowledge from Franklin to Facebook*, a book edited by the American Philosophical Society, and yet another paper is currently under review to be published as part of a special issue of *Berichte zur Wissenschaftsgeschichte*. I also published a paper in the BJHS together with a group of BSHS scholars who organised a digital science festival at the beginning of the Covid-19 pandemic. The paper reflects on the challenges of moving conferences online during a pandemic and climate emergency.

Societal Impact

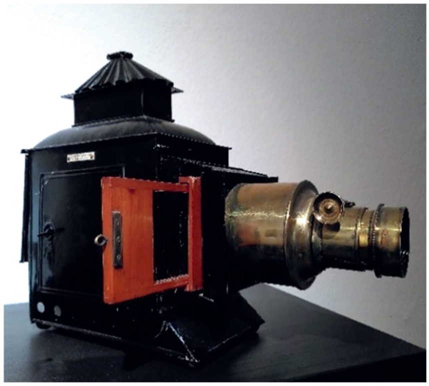
Involving non-academic audiences in my research is close to my heart and has been central to this PhD project. To some extent, research outreach was integrated in the PhD from the beginning through the *Worlds of Wonder* citizen science project (see Chapters One, Two and Five), which managed to attract ca. 2,400 online participants. The citizen scientists helped me classify and analyse some of my historical sources, and we learned about the history of microscopy together in the process. In the *Worlds of Wonder* chat forum, we exchanged ideas about how to improve the project workflow and what aspects of the history of microscopy we found particularly interesting. For example, some of the participants put together their own virtual collections of microscopy illustrations, including one of illustrations by female illustrators. One of the citizen scientists, Peter Mason, offered to write Python scripts that would enable me to analyse the data resulting from *Worlds of Wonder* in much more depth, which was a tremendous help and reminded me that although citizen scientists may not be professional researchers, they are often experts in other areas.

Worlds of Wonder, including an accompanying blog and Twitter account, made up the biggest part of my outreach activities, but there were several other projects I became involved in during the PhD. I gave a magic lantern lecture at the Maastricht PAS Festival in 2019, inspired by a magic lantern performance I had been part of during an internship at the University of Leicester (see Chapter Five), where I introduced the audience not only to my research, but also to the magic lantern, a historical slide projector. In 2020, I successfully applied for a masterclass on community-engaged research with Alan Irwin, which allowed me to present my research at a public panel discussion in Maastricht. Moreover, in 2021, I came in second in the *Bake Your Research!* competition organised by the Maastricht Young Academy. I had shared my research in the form of baked microscope slides, using melted candy as a mounting medium for chocolate specimens. The baking competition inspired me to further explore the potential of sensory research communication and encouraged me to (successfully) apply for a KNAW award for research communication in 2021, together with a whole group of FASoS colleagues interested in sensory research communication.

Throughout the PhD, I have also been acutely aware of the politics of research communication, thinking about whom we can (and should) share our research with, and how, and the consequences this may have for political decision making. In 2020, I co-founded the *Historians for Future* climate collective, which seeks to provide a historical perspective on the climate and biodiversity crisis, and which has by now launched a podcast and blog. Since 2020, I have also been a member of the digitalisation committee of the Duisburg city council, working to make sure that the city provides digital services that meet the needs of its citizens.

In my role as an advisory member of the committee I have certainly profited from my work on the digital infrastructures of participatory research.

The microscope slides I made for the *Bake Your Research!* competition, taking inspiration from Mary Ward's nineteenth-century slides, which were wrapped in emerald green paper.



The magic lantern I used for my 2019 PAS lecture on citizen science.

Looking Ahead

From October 2022, I will work as science editor for a start-up that combines tech education and tech journalism. The company helps other organisations navigate the digital transformation, figure out how digitalisation affects their established work processes, and empower employees to actively shape the digital future of their work. I am confident that both my PhD research and outreach activities have equipped me well to understand technological change in theory and practice. For example, the concept of user innovation (Chapter Four) will be helpful in understanding how employees can creatively use and adapt digital technologies to their needs. Likewise, the question of how knowledge can be shared at a distance will continue to be important in my new position, since being able to collaborate remotely has already profoundly changed the way we work and will continue to play a crucial role in the digitalisation of our workplaces. I feel lucky that, as science editor, I will be able to keep thinking and writing about technology, society, and knowledge exchange, and look forward to reaching out to new audiences and collaborators.

Summary

In 1887, the president of the British Postal Microscopical Society, J.W. Measures, declared that "the beginner is unable to learn from the books on the microscope all the minutiae of so fine an art as mounting [microscope specimens]."[1] The preparation of microscope slides, the observation of specimens, as well as the use (and production) of a compound microscope and its many accessories indeed required a high level of practical skill, or craft knowledge, which could only be gained through innumerable hours of training and was often difficult to translate into written instructions. Since skills require some manual dexterity and seem difficult, if not impossible, to codify in text, historians have so far tended to assume that learning skills from other scientific practitioners requires some form of on-site interaction. As the historian Myles Jackson explains in an article reviewing the scholarship on skill in the history of science, skills "are acquired through direct contact and personal observation of experimental technique."[2] Only more recently have historians, mostly early modernists, begun to question the assumption that acquiring skills requires historical actors to be co-present, a discussion that this dissertation extends to the history of microscopy in the late nineteenth century.

I argue that late-nineteenth-century microscopists developed ways of sharing even craft knowledge of microscopy remotely. The question of how that was possible lies at the heart of this dissertation. It asks how microscopists who hardly ever met in person managed to pass on their skills in microscopy, ranging from the making of observations and microscope preparations to the production of scientific instruments. I show that in order to learn microscopy at a distance, microscopists relied on trade and communication infrastructures that allowed for the sharing of skills. Skills may be difficult to translate into writing, but when we consider late-nineteenth-century infrastructures in all their diversity, drawing on a broad array of historical sources, we see that they made it possible to share not only texts but also images and objects, or replicate practical demonstrations in different places. This dissertation, therefore, challenges the common assumption that craft knowledge is primarily acquired from others on-site. At the same time, it invites us to explore the kinds of infrastructure that can accommodate craft knowledge and reconsider the role of infrastructure in sharing scientific skills within a community of practitioners.

So far, the literature on the history of microscopy has mainly been concerned with microscopy in the early modern age and the first half of the nineteenth

[1] Osborn, "Editorial – Postal Microscopical Clubs," 33.
[2] Jackson, "Labor, Skills, and Practices in the Scientific Enterprise," 902.

century, a time when the use of the microscope for scientific research was still controversial, and truth claims established with the help of the instrument much more contested than towards the end of the nineteenth century. I argue that if we want to understand how skills in microscopy were shared widely and across great distances, the second half of the nineteenth century deserves more attention. During that period, most microscopy societies were established, microscopy periodicals founded, and it was a time when the businesses of natural history and instrument dealers flourished due to an increased demand for microscopes at industrial and governmental laboratories, as well as educational institutions. Geographically, this dissertation first focuses on Great Britain and the United States, where a wealth of microscopy societies and periodicals helped diverse groups of learners to acquire skills in microscopy, before turning to the German lands and the rise of the Zeiss company in the 1870s and 1880s, which reconfigured, but also profited from, the knowledge infrastructures established by British and American microscopists.

Scholars working in the field of infrastructure studies, Susan Leigh Star, Karin Ruhleder and Geoffrey Bowker, among others, have shown that infrastructure, as long as it functions smoothly, is often barely noticeable, which poses a challenge to scholars who want to study it. However, we can analyse infrastructure by effecting an "infrastructural inversion," consciously foregrounding infrastructures that would otherwise remain in the background. [3] This dissertation argues that infrastructural inversion can also help us understand how microscopists exchanged craft knowledge at a distance. The historical actors in this dissertation depended on infrastructures to exchange a host of diverse objects, ranging from notebooks to microscope slides, instruments, and living microscopic animals. In trying to circulate such a diverse range of artefacts across long distances, microscopists had to make sure that both their skills in microscopy and infrastructures were perfectly attuned to the task. I show that a microscopist's skill in making observations, preparations or instruments was inseparable from their skill in building and using knowledge infrastructures. Consequently, infrastructural inversion allows us to examine not only infrastructures, but also the craft knowledge they helped microscopists to share.

Drawing on Helena Karasti and Jeanette Blomberg's work on infrastructure, the chapters in this dissertation achieve infrastructural inversion by "investigating moments of breakdown, following how members themselves engage in activities of infrastructural inversion, and following infrastructural traces in the material and technical environments."[4] The first strategy, investigating moments of controversy or breakdown, is probably the most widely known, building on Bowker and Star's observation that infrastructure becomes more noticeable when it stops

[3] Bowker and Star, *Sorting Things Out*, 34.
[4] Karasti and Blomberg, "Studying Infrastructuring Ethnographically," 251.

functioning. The second, looking at the actors' attempts at infrastructural inversion, is based on the premise that an infrastructure remains visible to at least some of its users: its maintainers, people whose task it is to build and maintain infrastructure. The third strategy, following infrastructural traces, means reconstructing the movement of objects through infrastructure, preferably objects that document or bear traces of collaborative practices. Together, Karasti and Blomberg's three ways of infrastructural inversion organise the historical chapters of this dissertation.

Chapter Two adopts Karasti and Blomberg's approach of following artefacts as they move through infrastructure. Beginning in the 1850s, the chapter follows a set of microscopy artefacts: illustrations of a phylum of microscopic animals called rotifers, or wheel animals. The chapter draws on historical data collected through the *Worlds of Wonder* citizen science project, which I organised as part of my PhD research. The project invited citizen scientists to help analyse historical microscopy illustrations, making it possible to follow rotifer illustrations and their makers, and identify reproductions of the same illustration in different publications. The chapter looks at how novel printing technologies and print distribution infrastructures enabled microscopists to share their observations of rotifers, and at the same time develop their observational skills. At a time when the reproduction of scientific publications was hardly restricted by international copyright law, scissors-and-paste printing abounded, with publishers reusing both texts and illustrations that had been published elsewhere. Scissors-and-paste printing made it possible for microscopists to adapt microscopy illustrations as part of their observational practice, for example by recombining illustrations with new texts and images. In that sense, rotifer illustrations were never quite stabilised through print. They continued to be used in (and were changed by) a researchers' observational practice, much like the messy, private sketches the historian Omar Nasim calls "working images," allowing observers to probe with the hand what is seen with the eye.[5] The chapter shows that observation was a craft that depended on the hand as much as the eye, making craftspeople, such as illustrators and natural history dealers, vital in sharing microscopy observations. Natural history dealers, for example, provided science educators with living microscope specimens to be observed in the classroom, and with illustrations and written descriptions of those specimens. This gave craftspeople an opportunity not only to shape what students of the life sciences saw through the microscope, but also to help them interpret their observations.

Chapter Three turns to a group of historical actors whose task it was to maintain the infrastructures microscopists relied on to produce and exchange microscope slides. The chapter looks at the British Postal Microscopical Society and

[5] See Nasim, *Observing by Hand*.

the American Postal Microscopical Club, whose officers and secretaries built postal networks that enabled their members to pass on slides and notebooks following a chain-letter system. Educating their members on how to make microscope slides was the primary purpose of the two postal microscopy organisations. The officers of the postal society and club articulated the work it took to establish their chain-letter networks in their notebooks, publications, lists of members, and in maps of postal circuits. Both organisations frequently addressed the infrastructures organising their work, which, according to Karasti and Blomberg's work on infrastructure, makes it easier for historians to study them. There was a sense among the members of the two postal organisations that their craft knowledge of how to make permanent slides was difficult to share without physical meetings. In response, they conceived of alternative ways to share their skills, which included the making of sketches in addition to texts, as well as attempts at reverse-engineering slides. Yet the society and club's postal networks remained fragile, depending on the reliability of their members to forward packages and keep the exchange going, while making sure that the slides forwarded would not break in transit. In order to deal with these vulnerabilities, regular reports on the activities of the postal society and club were published in microscopy periodicals. This helped to institutionalise the two organisations, centralise the postal exchanges, discipline unreliable or careless members, and share recommendations for the preparation of microscope specimens. The postal society and club managed to connect their members for at least several decades – the British Postal Microscopical Society exists to this day – and over time, the ability of a slide to travel postal networks without breaking became proof of its durability and helped to set the benchmark for other permanent preparations.

Chapter Four investigates a moment of controversy or breakdown, focusing on two stages of a fierce transatlantic debate in the 1870s, the "battle of the glasses." The battle was fought over the ultimate limit of resolution in a light microscope, which American immersion lenses had pushed further than many British microscopists deemed possible. The controversy not only exposed but directly affected microscopists' knowledge infrastructures, asking them to reconsider and adapt established communication mechanisms. At the same time, the controversy gave the German physicist Ernst Abbe an opportunity to become involved in the British microscopy community, share his research through the knowledge infrastructures that emerged during the controversy, and profit from innovations conceived of by his British correspondents. The chapter builds on the premise that the process of "amateurisation," a term used by Sam Alberti and others to describe British amateurs fashioning an identity for themselves in the 1860s and 1870s, went hand in hand with the establishment of infrastructures that served as a testbed for innovation in scientific instrument making: Ernst Abbe, working for the Zeiss company, profited from the infrastructures established by members of the Royal Microscopical Society.[6] Moreover, drawing on work in controversy studies and innovation studies, I argue that historians of science have studied controversy and innovation in some depth, but they have been less concerned with controversy *in* innovation. The history of the "battle of the glasses" shows that innovation can be deeply controversial, and that controversies shape the infrastructures that facilitate user innovation.

In order to provide answers to the research question of how geographically dispersed microscopists acquired skills in microscopy, **Chapter Five** draws together the main findings of the previous chapters. It argues that to share their craft knowledge of microscopy, microscopists began to use late-nineteenth-century infrastructures to their advantage, circulating slides, texts and illustrations, as well as living specimens, and conceiving of various ways of long-distance collaboration. In the process, microscopists themselves helped to build infrastructures which facilitated the exchange of craft knowledge. Around 1900, however, microscopists became less influential in the scientific community, and the chapter identifies some of the reasons of their decline. Finally, the chapter turns to the performative dimension of studying infrastructure. As researchers, we decide which infrastructures are worth following in our analyses, always foregrounding only some while others remain in the background. Wolfgang Kaltenbrunner has further developed this notion of performativity, describing infrastructural inversion as a "generative resource."[7] In his view, infrastructural inversion can be a creative tool, a way of reimagining and reconfiguring existing infrastructures. Applying Kaltenbrunner's concept of infrastructural inversion as a generative resource to this dissertation means to reflect on the generative potential of the infrastructures I built in my research, especially the ones I developed as part of the *Worlds of Wonder* citizen science project. The final chapter therefore examines how my research into late-nineteenth-century infrastructures shaped *Worlds of Wonder*, and vice versa, concluding this dissertation with a reflection on the past and present of participatory science and imagining its possible futures.

[6] See Alberti, "Amateurs and Professionals in One County."
[7] See Kaltenbrunner, "Infrastructural Inversion."

Samenvatting

In 1887 verklaarde de voorzitter van de British Postal Microscopical Society, J.W. Measures, dat "de beginner niet in staat is om alle details over de fijne kunst van het prepareren [van microscopische preparaten] uit boeken over de microscoop te leren".[1] Het prepareren van objectglaasjes, het observeren van preparaten, evenals het gebruik (en de productie) van een samengestelde microscoop en zijn vele toebehoren vereisten inderdaad een hoog niveau van praktische vaardigheid of ambachtelijke kennis, die alleen kon worden verworven door ontelbare uren opleiding en die vaak moeilijk te vatten was in geschreven instructies. Aangezien vaardigheden een zekere handigheid vereisen en moeilijk, zo niet onmogelijk, in tekst te codificeren lijken, zijn historici tot op heden geneigd aan te nemen dat het aanleren van vaardigheden van andere wetenschapsbeoefenaren een vorm van plaatselijke interactie vereist. Zoals de historicus Myles Jackson uitlegt in een artikel waarin hij een overzicht geeft van de wetenschappelijke kennis over vaardigheden in de geschiedenis van de wetenschap, worden vaardigheden "verworven door direct contact en persoonlijke observatie van experimentele technieken".[2] Pas recentelijk zijn historici, meestal vroegmodernisten, begonnen met vraagtekens te plaatsen bij de aanname dat het verwerven van vaardigheden de gezamelijke aanwezigheid van historische actoren vereist. Dit proefschrift breidt de discussie uit naar de casus van de geschiedenis van de microscopie aan het eind van de negentiende eeuw.

In dit proefschrift stel ik dat laat-negentiende-eeuwse microscopisten manieren ontwikkelden om zelfs ambachtelijke kennis van microscopie op afstand te delen. De vraag hoe dat mogelijk was, vormt de kern van dit proefschrift. Hoe slaagden microscopisten, die elkaar nauwelijks persoonlijk ontmoetten, erin om hun vaardigheden in microscopie door te geven, zowel wat betreft het doen van observaties, als het maken van microscooppreparaten en het produceren van wetenschappelijke instrumenten? Om microscopie op afstand te leren, waren microscopisten afhankelijk van handels- en communicatie-infrastructuren die het delen van vaardigheden mogelijk maakten. Vaardigheden zijn misschien moeilijk naar het schrift te vertalen, maar als we de laat-negentiende-eeuwse infrastructuren in al hun diversiteit bekijken, op basis van een breed scala aan historische bronnen, zien we dat de infrastructuren het mogelijk maakten om niet alleen teksten, maar ook beelden en objecten uit te wisselen, of praktische demonstraties op verschillende plaatsen na te bootsen. Deze dissertatie stelt daarom de gangbare veronderstelling ter discussie dat ambachtelijke kennis in de

[1] Osborn, "Editorial – Postal Microscopical Clubs," 33.
[2] Jackson, "Labor, Skills, and Practices in the Scientific Enterprise," 902.

eerste plaats van anderen ter plaatse werd geleerd. Tegelijkertijd nodigt dit onderzoek ons uit om de soorten infrastructuur te onderzoeken die gebruikt konden worden voor het delen van ambachtelijke kennis en om de rol van infrastructuur bij het delen van wetenschappelijke vaardigheden binnen een gemeenschap van beoefenaars te heroverwegen.

Tot nu toe heeft de historiografie van de microscopie zich voornamelijk beziggehouden met microscopie in de vroegmoderne tijd en de eerste helft van de negentiende eeuw. In deze periode was het gebruik van de microscoop voor wetenschappelijk onderzoek nog controversieel en waarheidsclaims die met behulp van het instrument tot stand kwamen waren veel meer omstreden dan ze dat op het einde van de negentiende eeuw zouden zijn. Als we willen begrijpen hoe vaardigheden in microscopie op grote schaal en over grote afstanden werden gedeeld, verdient de tweede helft van de negentiende eeuw echter meer aandacht. In die periode werden de meeste microscopieverenigingen en microscopietijdschriften opgericht. Bovendien was het een tijd waarin de bedrijven van natuurhistorische objecten en wetenschappelijke instrumenten floreerden als gevolg van een toegenomen vraag naar microscopen bij industriële- en overheidslaboratoria en onderwijsinstellingen. Geografisch gezien concentreert dit proefschrift zich eerst op Groot-Brittannië en de Verenigde Staten, waar een overvloed aan microscopieverenigingen en tijdschriften diverse groepen leerlingen hielpen om zich te bekwamen in de microscopie. Vervolgens verschuift de aandacht naar de Duitse landen en de opkomst van de firma Zeiss in de jaren 1870 en 1880, die de kennisinfrastructuren die door Britse en Amerikaanse microscopisten waren opgezet opnieuw vorm gaf, maar er ook van profiteerde.

Wetenschappers op het gebied van infrastructuurstudies, onder wie Susan Leigh Star, Karin Ruhleder en Geoffrey Bowker, hebben aangetoond dat infrastructuur vaak nauwelijks waarneembaar is zolang zij goed functioneert. Dat vormt een uitdaging voor wetenschappers die haar willen bestuderen. We kunnen infrastructuur echter analyseren door een "*infrastructural inversion*" (en infrastructurele omkering) te bewerkstelligen, waarbij infrastructuren die anders op de achtergrond zouden blijven, bewust op de voorgrond worden geplaatst.[3] Deze dissertatie stelt dat *infrastructural inversion* ook kan helpen te begrijpen hoe microscopisten ambachtelijke kennis uitwisselden op afstand. De historische actoren in dit proefschrift waren afhankelijk van infrastructuren om een groot aantal uiteenlopende objecten uit te wisselen, variërend van notitieboekjes tot microscoopglaasjes, instrumenten en levende microscopische organismen. Bij hun pogingen om zo'n grote verscheidenheid aan artefacten over grote afstanden te laten circuleren, moesten microscopisten ervoor zorgen dat zowel hun vaardigheden in microscopie als hun infrastructuren perfect op het delen van

[3] Bowker and Star, *Sorting Things Out*, 34.

kennis over grote afstanden waren afgestemd. Het blijkt dat de vaardigheid van een microscopist in het maken van waarnemingen, preparaten of instrumenten onlosmakelijk verbonden was met diens vaardigheid in het bouwen en gebruiken van kennisinfrastructuren. Bijgevolg stelt *infrastructural inversion* ons in staat om niet alleen de infrastructuren van microscopisten te onderzoeken, maar ook de ambachtelijke kennis die hand in hand ging met het gebruik van deze infrastructuren.

Puttend uit het werk van Helena Karasti en Jeanette Blomberg over infrastructuur, passen de hoofdstukken in dit proefschrift infrastructurele inversie toe door "momenten van ineenstorting te onderzoeken, te volgen hoe actoren zelf activiteiten van *infrastructural inversion* ontplooien, en infrastructurele sporen in de materiële en technische omgevingen te volgen".[4] De eerste strategie, het onderzoeken van momenten van controverse of ineenstorting, is waarschijnlijk de meest bekende, voortbouwend op de observatie van Bowker en Star dat infrastructuur meer opvalt wanneer zij niet meer functioneert. De tweede strategie, waarbij wordt gekeken naar de pogingen van de actoren tot infrastructurele inversie, is gebaseerd op de vooronderstelling dat een infrastructuur zichtbaar blijft voor ten minste een deel van haar gebruikers: haar beheerders, mensen met de taak de infrastructuur te bouwen en te onderhouden. De derde strategie, het volgen van infrastructurele sporen, houdt in dat de beweging van objecten door de infrastructuur wordt gereconstrueerd, bij voorkeur objecten die de sporen van samenwerkingspraktijken vertonen. De historische hoofdstukken in deze dissertatie volgen de drie manieren van infrastructurele inversie van Karasti en Blomberg.

In lijn met Karasti en Blombergs benadering volgt **hoofdstuk twee** artefacten die zich in de infrastructuur bewegen. Het hoofdstuk begint in de jaren 1850 en volgt een reeks microscopische artefacten: illustraties van een fylum van microscopische organismen, rotiferen genaamd, of wieldiertjes. Het hoofdstuk is gebaseerd op historische data die zijn verzameld via het *Worlds of Wonder* citizen science project, dat ik organiseerde als onderdeel van mijn promotieonderzoek. Het project nodigde burgerwetenschappers uit om historische microscopie-illustraties te helpen analyseren, waardoor het mogelijk werd om rotiferenillustraties en hun makers te volgen, en reproducties van dezelfde illustratie in verschillende publicaties te identificeren. In dit hoofdstuk wordt nagegaan hoe nieuwe druktechnieken en drukwerkdistributie-infrastructuren microscopisten in staat stelden hun waarnemingen van rotiferen te delen, en tegelijk hun observatievaardigheden te ontwikkelen. In een tijd waarin de reproductie van wetenschappelijke publicaties nauwelijks werd beperkt door de internationale wetgeving op het gebied van auteursrechten, was letterlijk knip-en-

[4] Karasti and Blomberg, "Studying Infrastructuring Ethnographically," 251.

plakwerk een wijdverbreid verschijnsel, waarbij uitgevers zowel teksten als illustraties hergebruikten die elders waren gepubliceerd. Knip- en plakwerk maakte het voor microscopisten mogelijk om microscopie-illustraties aan te passen als onderdeel van hun observatiepraktijk, bijvoorbeeld door illustraties opnieuw te combineren met nieuwe teksten en afbeeldingen. In die zin werden rotiferenillustraties nooit helemaal onveranderlijk door druk. Ze bleven gebruikt worden in (en werden veranderd door) de observatiepraktijk van een onderzoeker, net zoals de losse, persoonlijke schetsen die de historicus Omar Nasim "*working images*" noemt, waarmee waarnemers met de hand kunnen aftasten wat met het oog wordt gezien.[5] Het hoofdstuk laat zien dat waarnemen een ambacht was dat evenzeer afhankelijk was van de hand als van het oog, waardoor ambachtslieden, zoals illustratoren en natuurhistorische handelaren, van vitaal belang waren bij het delen van microscopie-observaties. Natuurhistorische handelaren voorzagen leraren in de natuurwetenschappen bijvoorbeeld van levende microscopische preparaten om in de klas te bekijken, en van illustraties en schriftelijke beschrijvingen van die preparaten. Dit gaf ambachtslieden de kans om niet alleen vorm te geven aan wat leerlingen van de biologische wetenschappen door de microscoop zagen, maar ook om hen te helpen hun waarnemingen te interpreteren.

Hoofdstuk drie richt zich op een groep historische actoren die tot taak hadden de infrastructuur in stand te houden waarop microscopisten vertrouwden om microscoopglaasjes te produceren en uit te wisselen. Het hoofdstuk behandelt de British Postal Microscopical Society en de American Postal Microscopical Club, waarvan de bestuursleden postnetwerken opbouwden die hun leden in staat stelden draagglaasjes en notitieboekjes door te geven volgens een systeem van kettingbrieven. Het hoofddoel van de twee postmicroscopie organisaties was hun leden te leren hoe ze microscoopglaasjes moesten maken. De functionarissen van de postvereniging en de club beschreven het werk dat nodig was om hun kettingbrief-netwerken op te zetten in hun notitieboekjes, publicaties, ledenlijsten, en in kaarten van postcircuits. Beide organisaties gingen vaak in op de infrastructuren die hun werk mogelijk maakte, wat het voor historici, volgens het werk van Karasti en Blomberg over infrastructuur, gemakkelijker maakt om ze te bestuderen. Onder de leden van de twee postorganisaties heerste het gevoel dat hun ambachtelijke kennis van het maken van permanente objectglaasjes moeilijk te delen was zonder fysieke bijeenkomsten. Als reactie daarop bedachten zij alternatieven om hun vaardigheden te delen, zoals naast teksten ook schetsen te maken. Ook onderzochten ze objectglaasjes via *reverse-engineering*. Toch bleven de postnetwerken van de vereniging en de club kwetsbaar, omdat ze afhankelijk waren van de betrouwbaarheid van hun leden om pakjes door te sturen en de

[5] See Nasim, *Observing by Hand*.

uitwisseling gaande te houden, en omdat de leden ervoor moesten zorgen dat de doorgestuurde objectglaasjes niet zouden breken tijdens het vervoer. Om deze kwetsbaarheden te ondervangen werden regelmatig verslagen over de activiteiten van de postvereniging en de club gepubliceerd in microscopietijdschriften. Dit hielp om de twee organisaties te institutionaliseren, de postwisselingen te centraliseren, onbetrouwbare of onzorgvuldige leden te disciplineren, en aanbevelingen uit te wisselen voor het prepareren van microscopische preparaten. De postvereniging en de club slaagden erin hun leden gedurende minstens enkele decennia met elkaar in contact te brengen – de Britse Postal Microscopical Society bestaat nog steeds – en na verloop van tijd werd het feit dat objectglaasjes postale netwerken konden doorkruisen zonder te breken gezien als een bewijs van hun duurzaamheid. Op die manier werden ze een maatstaf voor andere permanente preparaten.

Hoofdstuk vier onderzoekt een moment van controverse, waarbij de aandacht uitgaat naar twee stadia van een hevig transatlantisch debat in de jaren 1870, de "*battle of the glasses*". De strijd werd uitgevochten over de uiterste grens van resolutie in een lichtmicroscoop, die door Amerikaanse immersielenzen verder was opgeschoven dan veel Britse microscopisten voor mogelijk hielden. De controverse legde niet alleen de kennisinfrastructuur van de microscopisten bloot, maar had ook een directe invloed op hen en dwong hen de gevestigde communicatiemechanismen te heroverwegen en aan te passen. Tegelijkertijd bood de controverse de Duitse natuurkundige Ernst Abbe de kans om betrokken te raken bij de Britse microscopiegemeenschap, zijn onderzoek te delen via de kennisinfrastructuren die tijdens de controverse ontstonden, en te profiteren van innovaties die door zijn Britse correspondenten werden bedacht. Het hoofdstuk gaat uit van de premisse dat het proces van "*amateurisation*", een term gebruikt door Sam Alberti en anderen wetenschapshistorici om te beschrijven hoe Britse amateurs in de jaren 1860 en 1870 een identiteit voor zichzelf ontwikkelden, hand in hand ging met de oprichting van infrastructuren die dienden als proeftuin voor innovatie in de wetenschappelijke instrumentenbouw: Ernst Abbe, werkzaam voor de firma Zeiss, profiteerde van de infrastructuren die door leden van de Royal Microscopical Society waren opgezet.[6] Voortbouwend op het werk van controversestudies en innovatiestudies, stel ik bovendien dat wetenschapshistorici controverses en innovatie tot op zekere hoogte hebben bestudeerd, maar dat zij zich minder hebben beziggehouden met controverses *in* het innovatieproces. De geschiedenis van de "*battle of the glasses*" laat zien dat innovatie zeer controversieel kan zijn, en dat controverses vorm geven aan de infrastructuren die gebruikersinnovatie mogelijk maken.

[6] See Alberti, "Amateurs and Professionals in One County."

Om een antwoord te geven op de onderzoeksvraag hoe geografisch verspreide microscopisten vaardigheden in microscopie verwierven, worden in **hoofdstuk vijf** de belangrijkste bevindingen uit de vorige hoofdstukken samengebracht. Het stelt dat microscopisten, om hun ambachtelijke kennis van microscopie te delen, de laat-negentiende-eeuwse infrastructuren in hun voordeel gingen gebruiken, door microscoopglaasjes, teksten en illustraties, evenals levende organismen, te laten circuleren en verschillende manieren van samenwerking over lange afstand te bedenken. In dit proces hielpen de microscopisten zelf mee aan de opbouw van infrastructuren die de uitwisseling van ambachtelijke kennis vergemakkelijkten. Rond 1900 werden de microscopisten echter minder invloedrijk in de wetenschappelijke gemeenschap, en het hoofdstuk identificeert enkele redenen van hun terugval. Ten slotte gaat het hoofdstuk in op de performatieve dimensie van het bestuderen van infrastructuur. Als onderzoekers beslissen we welke infrastructuren het waard zijn om in onze analyses te volgen, waarbij we altijd slechts enkele op de voorgrond plaatsen terwijl andere op de achtergrond blijven. Wolfgang Kaltenbrunner heeft deze notie van performativiteit verder ontwikkeld en omschrijft infrastructurele inversie als een "*generative resource*".[7] Volgens hem kan *infrastructural inversion* een creatief instrument zijn, een manier om bestaande infrastructuren opnieuw te bedenken en te configureren. Het toepassen van Kaltenbrunners concept van infrastructurele omkering als *generative resource* op dit proefschrift betekent ook nadenken over het generatieve potentieel van de infrastructuren die ik in mijn onderzoek heb gebouwd, in het bijzonder de infrastructuren die ik heb ontwikkeld als onderdeel van het *Worlds of Wonder* burgerwetenschapsproject. Het laatste hoofdstuk onderzoekt daarom hoe mijn onderzoek naar laat-negentiende-eeuwse infrastructuren *Worlds of Wonder* heeft gevormd, en vice versa. Het sluit dit proefschrift af met een reflectie over het verleden en heden van participatieve wetenschap en een schets van de mogelijke toekomst ervan.

[7] See Kaltenbrunner, "Infrastructural Inversion."

Curriculum Vitae

Lea Beiermann was born on August 23, 1992, in Düsseldorf, Germany, where she completed her primary and secondary education. She graduated with a BA in Creative Writing and Cultural Journalism (*with distinction*) from Universität Hildesheim in 2015 and an MScRes in Cultures of Arts, Science and Technology (*cum laude*) from Maastricht University in 2017. During her master's programme, she interned with the ConSciCom research group at the University of Leicester (Constructing Scientific Communities in the Nineteenth and Twenty-First Centuries), where she learned to analyse historical scientific periodicals and operate a magic lantern. Her master's thesis explored the role of London's periodical press in building a microscopy community in the late nineteenth century. For her thesis, she was awarded the UM Thesis Prize of the *Stichting Wetenschapsbeoefening*, Maastricht University, in 2018. Her PhD project, funded by an NWO PhDs in the Humanities Grant, gave her an opportunity to study late-nineteenth-century microscopy in more depth (2018-2022). As part of her PhD, she completed the graduate training programme of the Netherlands Graduate Research School of Science, Technology and Modern Culture (WTMC). In 2022, she was a visiting PhD candidate at the Department of History and Philosophy of Science (HPS) of the University of Cambridge. For her paper on the microscope slide exchange of the American Postal Microscopical Club, based on Chapter Three of this PhD dissertation, she received the 2020 Singer Prize of the British Society for the History of Science.