Diseña 18

Navigating Dimensions across Materials *and* History: Scale as *a* Lens *to* Understand Dynamic *and* Cumulative Sociotechnical Relationships

How to cite this article: Spero, E. F., & Ortiz, C. (2021). Navigating Dimensions across Materials and History: Scale as a Lens to Understand Dynamic and Cumulative Sociotechnical Relationships. *Diseña*, (18), Article.1.
https://doi.org/10.7764/disena.18.Article.1

DISEÑA | 18 |
JANUARY 2021
ISSN 0718-8447 (print)
2452-4298 (electronic)

Original Research Article
Reception ☑
JAN 04 2021
Acceptance ☑
JAN 25 2021

Spanish translation here

Ellan F. Spero
Massachusetts Institute of Technology
Station1

Christine Ortiz
Massachusetts Institute of Technology
Station1

ABSTRACT

Through the lens of scale, this paper combines knowledge and perspectives from the history of technology and materials science and engineering to examine the materiality of the ubiquitous technological systems that are so often hidden in the everyday. The simultaneously exceptional and prosaic case of materials underpinning water filtration is examined in a 19th century manufacturing city in the United States. An analysis related to materials structure-property-processing-performance correlations is integrated with historical approaches to technological landscapes, the co-construction of use and value, and narratives of progress. This study provides insights into the dynamic social and material relationships that change across scales, as well as into mechanisms and cumulative influences of material constituents in larger sociotechnical systems. This contribution is incorporated within a framework for socially-directed science and technology, and its implementation in new and existing higher education institutions is discussed.

Keywords
Materials
Scale
Infrastructure
Socially-directed science and technology
Pedagogy

AUTHORS

Ellan F. Spero— Bachelor of Science and Master of Science in Fiber Science and Apparel Design, Cornell University. Master of Arts in Museum Studies and Textile Conservation, Fashion Institute of Technology. Doctor of Philosophy in History, Anthropology, Science, Technology and Society, Massachusetts Institute of Technology (MIT). Spero is an Instructor at MIT in the Department of Materials Science and Engineering, and Co-Founder and Professor of the Practice at Station1, a nonprofit higher educational institution focused on socially-directed science and technology. Research areas of focus include narratives of progress, systems of production, academic-industrial ecosystems, and socio-material infrastructures. Spero is the author of 'The Tua Valley in Transition, Symbol and Technological Landscape' (with H. S. Pereira; CEM *Cultura, Espaço e Memória / Culture, Space & Memory*, N° 7), 'A Garden City for Progress and Harmony: Singapore at the Osaka 1970 Expo' (in S.G. Knowles and A. Molella eds.; *World's Fairs in the Era of the Cold War*; University of Pittsburgh Press, 2019), and 'An Entrepreneurial Opportunity in Process: Creating an Industrial Fellowship in Early Twentieth Century America' (*Management and Organizational History*, Vol. 12, N° 3).

Christine Ortiz— Bachelor of Science in Materials Science and Engineering, Rensselaer Polytechnic Institute. Masters of Science and Doctor of Philosophy in Materials Science and Engineering, Cornell University. Ortiz is the Morris Cohen Professor of Materials Science and Engineering at the MIT Department of Materials Science and Engineering, and founder of Station1, a nonprofit higher education institution focused on socially-directed science and technology. Research areas of focus include multiscale materials design and mechanics, socio-resilient approaches to materials development, biological materials, materials and nanotechnologies, materials modeling and simulation, high-resolution microscopy of materials, biological and bio-inspired materials. Ortiz is the author of over 195 scholarly publications including, 'Bioinspired Structural Materials' (with M. C. Boyce, *Science*, Vol. 319, N° 5866), 'Multifunctionality of Chiton Biomineralized Armor with an Integrated Visual System' (with L. Li, et al., *Science*, Vol. 350, N° 6263), and 'Hierarchical Structural Design for Fracture Resistance in the Shell of the Pteropod *Clio pyramidata*' (with L. Li, and J. C. Weaver, *Nature Communications*, 6, 6216).

Navigating Dimensions across Materials and History: Scale as a Lens to Understand Dynamic and Cumulative Sociotechnical Relationships

Ellan F. Spero
Massachusetts Institute of Technology
Department of Materials Science and Engineering
Cambridge, USA
Station1
Lawrence, USA
efs8@mit.edu

Christine Ortiz
Massachusetts Institute of Technology
Department of Materials Science and Engineering
Cambridge, USA
Station1
Lawrence, USA
cortiz@mit.edu

PERSPECTIVES ON SCALE ACROSS MATERIALS AND HISTORY

This paper combines knowledge and perspectives from the history of technology and materials science and engineering to examine, through the lens of scale, the materiality of the ubiquitous technological systems that are so often hidden in the everyday. We consider the simultaneously exceptional and prosaic case of materials that were critical components of water filtration, as developed in the late 19th century in a manufacturing city in the United States. The value of this type of historical analysis of socio-technical systems is then framed within the practice of socially-directed science and technology research and education.

Scale is a powerful lens to bring focus to the social and technical dimensions of the material worlds that surround us. It can help us assess the challenges of the present, while grounded in the past, and looking further ahead in order to shape a more sustainable and equitable future. Engaging scale – whether as length, mass, volume, density, temperature, or time – is a richly productive mode of inquiry for historians, scientists, engineers, and designers. Here, we focus on dimensional scale, noting that approaches to demarcation, crossing, visualization, or manipulation may vary as appropriate to the respective disciplinary modes of inquiry. To think across dimensions is to intentionally engage in perspective-shifting, just as thinking across disciplines can be a voyage between the familiar and the as-yet-unknown, amassing evidence, building tacit knowledge, and stretching the imagination along the way.

Scale has long underpinned the multidisciplinary field of materials science and engineering (MSE) since its emergence as a formal academic discipline at the beginning of the 20th century. A convergence of scales took place through the hybridization of atomic and molecular-level studies within physics and chemistry with the technological manipulation of matter in engineering fields, thus spanning practices of research and development across disciplines (i.e., physics, chemistry) (Bensaude-Vincent, 2016). MSE involves

> the structure and composition of a material, including the type of atoms and their arrangement, as viewed over the range of length scales (nano-, micro-, meso-, and macro-scale); the synthesis and processing by which the particular arrangement of atoms is achieved; the properties of the material resulting from the atoms and their arrangement that make the material interesting or useful; the performance of the material, that is the measurement of its usefulness in actual conditions, taking account of economic and social costs and benefits. (Flemings, 1999, pp. 1–2)

This disciplinary framework was conceptually visualized in 1986 in the form of a tetrahedron with these integrated components positioned at the vertices (Flemings, 1986). The trajectory of MSE has been heavily influenced by the development and availability of specialized experimental instruments and computational tools, which play a key role in creating communities of practice, often focused around particular accessible scales (Mody, 2011). Both narratives of scale and new methods broadening research capabilities across a wider range and types of scales drove the field, for example in the noteworthy cases of polymers (Perkins, et al., 1994; de Gennes, 1979) and nanotechnology (Binnig et al., 1986; Drexler, 1986; Feynman, 1960). In recent decades, experimental and computational capabilities have continued to advance, as well as aspirational 'materials-by-design' narratives, which has amplified emphasis on interrogating differential structure-property-processing-performance relationships as a function of scale, and driving efforts towards integration across scales towards both foundational knowledge and materials development (Jain et al., 2013; Martin-Martinez & Buehler, 2020; Ortiz & Boyce, 2008; Oxman et al., 2015; van Anders et al., 2015).

Materials integrate with, are embedded within, and influence the physical, social, cultural, and ideological human world at larger scales. They constitute and determine the functionality of assemblages, infrastructures, and systems, which have been a focus of civil engineering and architecture (De Wolf et al., 2020; Fivet & Brütting, 2020). The subfield of the materials science of material culture established a foundation, inherently involving a multiplicity of scales, for connecting the MSE disciplinary framework of structure-property-processing-performance relationships with archaeological, anthropological, and art historical knowledge through the scientific investigations of the materials technologies in the context of cultural practices grounded in the human sciences (Hosler, 1988; Lechtman, 1994). This research profoundly addresses the long history of materials and human culture predating the written record. The ubiquity of materials also draws increasing concern in relation to the large scale of planetary damage caused by them in terms of climate change, decrease in biodiversity, and proliferation of pollution and waste (United Nations Development Programme, 2020). Yet at the same time, materials are often viewed as critical to future aspirations for societal impact through the design of more sustainable, safer, robust, resilient, unique, useful, and potentially life-saving properties.

Scale also plays a major role in historical analysis in multiple ways. Historians are most likely to engage with scale in a temporal context, through periodization and the analysis of change, or not, over time. Increasing awareness of the contemporary climate crisis also draws particular attention to the importance of scale for historians of science and technology. Recent work on the Anthropocene especially focuses attention on the act of thinking with time, calling for "an analogous suppleness for time scales, from the nanosecond to the eon and everything in between" (Yang & Daston, 2017, p. 22). Building upon an approach from the history of ideas, the focus on scale might also serve to disrupt linear narratives, without "occlusion of one reference frame by another" (Coen, 2016, p. 312). Often, though not exclusively, the physical scale is grounded in human proportions and experience, as historians reconcile the commensurate dimensions of individuals, organizations, and societies. Technologies often serve as extensions of human senses or capabilities into previously inaccessible dimensions, with instruments such as microscopes, telescopes, and transport in extreme environments. Physical proximity to large scale technologies may even inspire awe (Nye, 1994).

Materials play important roles in the history of technology, as constituents and primary objects of study. They are linked to foundational concepts and inquiry into processes of design, use, and proliferation of technologies, which reflect, or even reinforce existing power relationships whether in households (Cowan, 1983) or large regional systems (Hughes, 1983). The focus on the materiality of technologies and their places of production, can reveal and bring focus to embedded social structures such as gender and power relationships (Bray, 1997). They are key factors in the ways that we study and interpret things and material cultures across science, technology, and art (Daston, 2004). The material form of technological objects can provide insight into the relational processes of social, cultural, and technological factors within them (Bijker et al., 2012). Through a focus on materials, it is possible to highlight the processes of expertise and professionalization, design choices, and functions both symbolic and technical (Handley, 2000; Lintsen et al., 2017; Ndiaye, 2007; Slaton, 2001). Materials technologies are central to the historical understanding of use, reuse, and waste (Finlay, 2003; Oldenziel & Trischler, 2016; Thorsheim, 2016; Zimring, 2005, 2017). As constituents of infrastructure materials, they can serve to highlight tensions between innovation and maintenance (Edgerton, 2007; Vinsel & Russell, 2020), and physical and social structures of community (Keating, 1994). The interplay between engineering, design, urban planning, and materials is especially apparent in systems of sanitation and hygiene which interface between technology, environment, and public health (Hansen, 2018; Melosi, 2000; Seewang, 2019). The ways that stories of materials are told matter, especially within narratives of progress, whether portrayed as new or old, innovative or traditional, or perhaps outside of binary categories all together (Dreicer, 2000, 2010). They can also provide a valuable window into how engineers, designers, and users navigate identities of modernity (Slaton, 2020).

The relationships between technologies and place provide a foundation for a focus on the materials embedded in them. Building upon the literal idea of landscape as "a composition of man-made or man-modified spaces to serve as infrastructure or background for our collective existence" (Jackson, 1984, p. 8), and drawing upon landscape as both an object and a process, technologies of landscape may be considered cultural rather than natural (Nye, 1999). Within this framing, landscape is a dynamic set of relationships, "part of the infrastructure of existence (…) inseparable from the technologies that people have used to shape land and their vision" (Nye, 1999, p. 3). Technologies and landscape taken together are not opposites or solely objects, but rather entangled processes. The concept of technological landscape is employed by historians of technology to draw attention to slow structural change accumulation of interconnected practices and artifacts (Bray, 2016; Lindqvist, 2011), and linked processes of transformative construction and subsequent 'naturalization' over time (Spero, 2013; Spero & Pereira, 2016). These interpretations of technological landscape both emphasize the connections, continuities, and complexities, whether between overlapping older and emerging technologies (Lindqvist, 2011) or the often problematic but nevertheless deep interconnectedness of human and non-human actors in the shaping of place (Spero, 2013; Spero & Pereira, 2016). By bringing attention to the material traces of particular embedded technological systems, be they subterranean filtration systems, railway lines, dams, or agricultural terraces, we may also have a heightened awareness for design choices and functionalities that are enduring or slow to change.

INTEGRATING METHODOLOGIES AND CONCEPTUAL FRAMEWORKS ACROSS HISTORY AND MATERIALS

The historical materials analyzed in this research include physical and digital manuscripts, photographs, and collections of published works. Unique materials in the collections of the Lawrence History Center (formerly Immigrant City Archives) included an extensive photograph collection documenting the construction of the water filtration system and other aspects of water infrastructure in the city (*Photographs of Water Filtration System Under Construction, ca. 1893-1910*), city atlases (*Lawrence City Atlases, 1875, 1888, 1906, 1926, 1938*), photographs of the cityscape and shoreline (*Aerial and Panoramic Photographs, ca. 1850-1920)*, oral history (Barker, 1989), documents and published works related to the engineering work of the Essex Company, Lawrence Experiment Station (LES), and later William X. Wall Experiment Station (*Engineering Records, 1845-1987*), and annual reports and city documents (*Lawrence City Documents, 1846-1913*). Collections held at the Massachusetts Institute of Technology (MIT) included manuscript collections relevant to scientists and engineers affiliated with both MIT and LES: Allen Hazen (*Allen Hazen Papers, 1883-1974*), William T. Sedgwick (*William T. Sedgwick Correspondence, 1893-1908*), and Hiram Francis Mills (Mills, 1912-1921), and Reports to the President (*Massachusetts Institute of Technology. Office of the President, 1871-1930*). Published works held digitally included a report on the work of the LES, as exhibited at the World's Columbian Exposition held in Chicago in 1893 (Massachusetts State Board of Health, 1893), journal articles related to water works, sewage, and sanitary science in the region (Eddy, 1930; Massachusetts State Board of Health, 1887), including the work of researchers affiliated with the LES (Bailey & Hazen, 1876; Burgess, 1915; Clark, 1907, 1909, 1927; Fuller, 1894; Hazen, 1897, 1907, 1910; H. Mills, 1893; Sedgwick, 1906, 1922).

Drawing upon visual analysis of urban, technological, and construction photography as historical evidence (Kammen, 2007; Maynard, 1997; Spero & Pereira, 2016; Weiss, 2020), images were selected and included in this paper to illustrate key integrative concepts related to scale, materials, construction, and scientific and technological narrative. Contemporary perspectives and conceptual frameworks in materials science and engineering were integrated with the historical archival analysis, including multiscale structure and imaging of materials (Estrin et al., 2019; Ortiz & Boyce, 2008), multiscale mechanics of granular materials (Ulm et al., 2007), multiscale computational simulations of materials (Li et al., 2012; Martin-Martinez & Buehler, 2020), and multiscale fabrication of materials (Browning et al., 2013; Lin et al., 2014; Oxman, 2010). Cross-disciplinary integrative analysis and intentional practices of dialogue, reflection, translation, and integration of concepts and modes of inquiry (Strober, 2011) between MSE and history of technology were used throughout the research process.

MATERIALS ACROSS SCALES IN TECHNOLOGICAL LANDSCAPES: AN INTEGRATIVE CASE STUDY OF THE MANUFACTURING CITY OF LAWRENCE, MASSACHUSETTS

Through the lens of scale, this study examines the mechanistic and aggregated influence of material constituents in larger systems, together with scale-dependent variable sociotechnical relationships. Building upon the concepts of technological landscape, we explore an integrated case study of the role of materials technologies and social impact in sand-based water filtration developed and employed in Lawrence, Massachusetts, at the end of the 19th century. Situated on the Merrimack River, once navigated by the Pennacook peoples before the transformation of the shoreline into later-day Lawrence (Dorgan, 1918; Stewart-Smith, 1999), this American city, like many other industrial centers, was, and continues to be, a place intimately tied to water (Hearn, 2014; Malone, 2009; Molloy, 1980). Built-up as a hydro-powered textile manufacturing center, the city grew quickly into a densely packed production center with residents newly arrived from regional farms, as well as from across the ocean, a melting pot for numerous languages and cultures. Linked to this quite visible role of the river as a power source was also a more hidden role in public health, only made explicit in the typhoid epidemic in the 1890s that impacted cities up and down the river. Although Lawrence shared much in common with other afflicted manufacturing cities, it was uniquely home to a laboratory that was the first of its kind in the United States, the Lawrence Experiment Station (LES). The work on water quality performed in Lawrence was to play an instrumental role not only in the recovery of the city, but also to set the standard for water filtration more broadly in the nation and beyond.

Scale is often a determinant of what is hidden or revealed. For example, when working at a large scale, underlying factors that may be too small to easily identify, but whose influence manifests in the macrosystem, may remain hidden. Likewise, when focused on a very small scale, the context of the system as a whole might also be easily obscured. At the city scale, this

Figure 1: Panoramic photograph of the 'City of Lawrence,' 1909 (Lawrence, Massachusetts). Source: Lawrence History Center 1985_138_002.

panoramic photograph (Figure 1) focuses attention on a single moment captured in the life of this particular place in 1909, the frozen flowing river, and the billowing factory smokestacks in mid-air. Even at this large scale, materials (e.g., brick, stone, iron, mortar, concrete, etc.) can be observed and understood as markers of this industrial city. The enormity of the built infrastructures evokes an understanding of the magnitude of materials utilized in its construction, as well as the expertise needed in their selection, design, and processing. Connected to the visible are hidden infrastructures (e.g., underwater or underground canal, pipes, and other water and hydropower infrastructure and systems, bridge support structures, etc.). At these large scales, materials are aggregated and assembled to form the visible static load-bearing structural assemblages, such as factory manufacturing buildings and hidden dynamic infrastructures concerning hydropower, water transport, and purification.

Within the frame of the technological landscape, we are attuned to the complexities and long transitions between technologies (Bray, 2016; Lindqvist, 2011). Many of these material elements endure, some have been maintained to retain their original functionality, others are retrofitted for new uses, and others yet fade into disuse. We consider the materials and processes at the multiple interfaces of water, stone, concrete, and sand. The Great Stone Dam (Figure 1, top left), the canal systems, and hydropower engineering structures built by the Essex Company to power the mills, spurred the economic growth of Lawrence as a manufacturing hub (Smith 1947; Hearn, 2014; Molloy, 1980). In 1909, when this image was captured, the dam had already been in operation for more than fifty years, and although not the primary source of power for the city, it remains in active operation with technologies for fish passage to lower the impact to the ecosystem (Lawrence Hydroelectric Project, 2020; Molloy, 1980). Hidden below the waterline of the canals, and underneath many of the remaining large brick structures, once dynamic mechanical systems that powered the works inside are stationary. However, within these remaining walls, through renovation and maintenance other types of uses continue, including manufacturing but also residential, entrepreneurial, educational, artistic, and community organizations.

At the civil engineering scale, Figure 2a provides a photograph of the water filtration system in the process of construction in 1906. This unique photograph details both the disorder of constituent raw materials and disposable materials, and the exposed emerging order of partially assembled infrastructures soon to be hidden underground and embedded in and interfacing with the natural landscape. Underlying the engineering aims of scale-up of known mechanisms and properties to manifest in func-

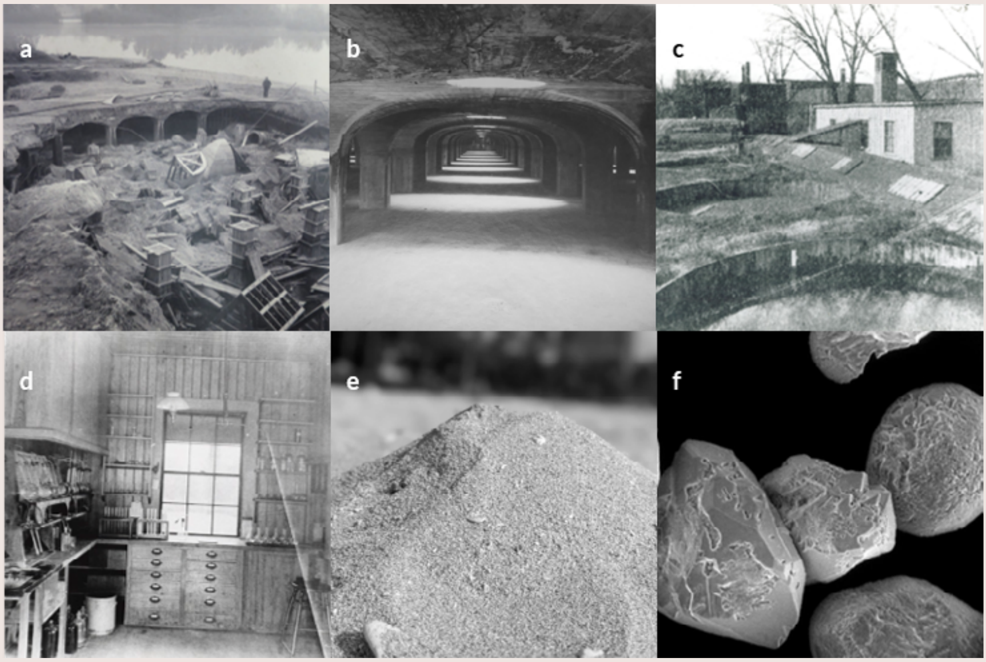

Figure 2: Multiscale view of water filtration and infrastructure materials, structures, systems.
a) Construction of water infrastructure system, 1907, Lawrence, Massachusetts. Source: Lawrence, History Center 'Water Filtration Construction Photographs' ICA 90.148.14A April 4th, 1907.
b) Internal view of covered sand filtration system, 1907, Lawrence, Massachusetts. Source: Lawrence History Center 'Water Filtration Construction Photographs,' November 4th, 1907, LW2012.194.014.
c) External view of the Lawrence Experiment Station, Lawrence, Massachusetts. Source: Lawrence History Center.
d) Interior View of the Lawrence Experiment Station, Lawrence, Massachusetts. Source: Lawrence History Center, 2002_063_476.
e) Photograph of a sandpile. Source: Brian J. Tarricone.
f) Ottawa sand, a standard material used in civil engineering tests, electron microscope image. Source: NASA/MSFC, NASA ID 0003830.

tional infrastructures exists expertise, knowledge, and decisions regarding materials selection, design, and processing. This photograph is a reminder of the ubiquity of sand, while its selection for use in water filtration systems was based on its desirable material properties. In the same frame, we see sand as both: a valuable technical material that has been measured as well as carefully monitored and maintained through periodic washing and relied upon for the health of the city, and as a discardable waste product that will have to be removed in the form of construction debris. The lone figure at the upper edge of the ground layer gives us a sense of the size of the project, and prompts inquiry into the embedded labor and knowledge hidden in each of these images, for example, material transport, assembly, and testing. It prompts intrigue around the underlying engineering and aesthetic choices, not only in the construction of this place itself, which few people would ever experience, but also its photographic documentation, which would serve as the primary mode of a future encounter. This person positioned above the construction site also foreshadows how the site might be interpreted as re-naturalized once complete, a feature of a technological landscape hidden within the mundane (Spero, 2013; Spero & Pereira, 2016). For the most part, this system was designed from the outset to be covered by earth, its workings hidden from view. In this case, the hidden works of sand, gravel, concrete, and pipes were key factors to the success of the design. When viewed from the human-scale, and also at a larger systems level, invisibility may serve itself as a marker of well-functioning materials infrastructure. These complex and critical socio-technical systems are often hidden from public view, literally underground, underfoot, or obscured in plain sight against the background of the mundane. Although often unnoticed, there are also systems of expertise in materials, design, monitoring, and maintenance that work to constantly avert disruption, or worse, in the everyday landscape.

At a smaller scale of individual infrastructure components, the pristine and fully assembled subterranean gallery of the covered filter beds (Figure 2b), designed to weather frigid New England winters, appears to stretch on with infinite repetition. Here, in a single frame, the observed materials constitute two different types of infrastructure: the static, load-bearing solid arches in proximity to the granular sand which chemically and biologically interface and dynamically interact with water and its contaminants. The individual grains are obscured and even blur together at this scale, producing the façade of a solid continuum that hides the mechanistic origins of the unique properties of granules related to water filtration.

At the laboratory scale, the modest timber structure of the original Experiment Station comes into focus (Figures 2c and 2d). This former building of the hydro-focused Essex Company was itself a place of convergence of material scales and for prototyping as a foundation for scale-up. Housed within this intermediary structure were microbes, sand, instruments, and humans, alongside prototype filter assemblies on the nearby grounds. The small community of researchers was connected to the then-nascent Massachusetts Institute of Technology in Boston, which was also contained within a single building at the time before relocating to its current Cambridge location in 1916 (MIT Office of the President, 1916). This proximity fostered emerging cross-disciplinary scholarship and interchange among chemistry, biology, bacteriology, mining, and metallurgy (the precursor to the contemporary department of materials science and engineering), civil engineering, architecture, and epidemiology leading to the emergence of sanitary science, sanitary engineering, and public health (Goldblith, 1995; Viseltear, 1988), all served as intellectual foundations for the Lawrence Experiment Station.

At the microscale, both bacteria and granules of sand, integral to the work of the LES, became visible. With the integration of bacteriology, the microscope went from an 'unfamiliar tool' hidden in plain sight on an upper shelf yet "never [had] been employed in laboratory routine," to a core tool in sanitary science at the LES (Winslow, 1953, p. 17). Although sand was the most widely employed material, the LES worked with parametric studies of materials including sand ranging from coarse (0.48 mm) to fine river silt (0.04 mm), with coarse crushed stone, gravel, coke, and clinkers also used in filtration experiments (Figure 2c) at the laboratory (Clark, 1909; Hazen, 1897). A key concept for the success of the test filters was the long timeframe for the experiments. In 1909, the twenty-year report chronicled that some of the filters had been in use since the opening of the Station, and many showed improved performance with time. Sand was both prosaic in its ubiquity, and 'leading edge' in the way that it was deployed as standardized filtration media with highly controlled dimensions. The unique and complex physics, involving surface interactions such as friction, adhesion, and molecular adsorption, underlying the macroscale properties of sand as a granular material, served as a foundational point of origin for this entire multiscale sociotechnical system. Sourced from nearby Gale's Hill, for the first filter system for the city in 1879, the expense to the city for this 'worthless material' carted by man and horse, and sorted by particle size for deployment in the filter beds, was labor alone (Marble, 1880).

MATERIALS AS CONSTITUENTS OF SOCIOTECHNICAL NARRATIVES ACROSS SCALES

Throughout the physical traces of the technological landscape embedded in a given place, are the narratives that are shaped by the people who created, maintained, and used them. Indeed, even people far away, who observe only from a distance, can contribute to the narratives of that place and its infrastructure. The stories of the city of Lawrence were, and often still are, connected to the health of the river and its industry. Indeed, the story of the LES traveled throughout the US and internationally both, through the circulation of papers or by the researchers themselves. In an exhibit that spanned multiple areas, the Massachusetts State Board of Health featured the LES at the prestigious World's Columbian Exposition in Chicago in 1893. The display heralded this work as "the first of the kind established in America," and included a model of the building, photographs, charts, sands, sewages, effluents, and sections of filters (Massachusetts State Board of Health, 1893, p. 3). An annex also included the plans for the filter system designed by Hiram Mills which was then still under construction (Massachusetts State Board of Health, 1893).

Specifically designed as 'an industrial community,' as reported in the 1912 Lawrence Survey, the city shared 'a typical modern problem' with countless other industrial cities, balancing "the conduct of manufacturers in a manner to secure prosperity on one hand, and the welfare of working people on the other" (Rowell, 1912, p. 15). This expression of the tensions between the specificity of place and the generalizability of specific types of challenges across geographies, in particular the often-competing interests of economic growth and public welfare, endure in Lawrence just as in many other global cities economically grounded in industrial production. Urban manufacturing centers such as these can offer newcomers the hope of social mobility, yet also face stubborn social and economic challenges that so typically accompany industrial growth and decline. The narratives of technological progress, production, prosperity, and unrealized potential are woven into the very fabric of the city's history. Linked to a hydro-powered system capable of realizing a high output of textile production, it was an inequitable social system heavily reliant on low wage labor.

Indeed, this city on the Merrimack was not just the home to pioneering water research translated into an advanced municipal water purification system. It was also the site of the infamous 1912 "bread and roses strike" (Cahn, 2005; Forrant & Grabski, 2013; Watson, 2005). Not surprisingly, the drama of harsh working conditions and the impact of the strike on working-class families attracted negative attention across the nation and beyond. In response, Laura Prescott, a Lawrence public school teacher, asked her pupils to share something positive that they knew was true about their hometown with other children in a different part of the country. Marion Barker, then nine-years-old, shared her story with a child who lived in Provo, Utah. She highlighted her pride in the invisible, subterranean, yet critical water filtration system and its importance to her daily life (Barker, 1989). The choice of a child to highlight a technological feature of her hometown, and still find it noteworthy when telling her oral history nearly 80 years later, serves to underscore its importance in daily life. She and her classmates had visited the filter system and learned about it in school, along with being told stories about the critical role filtration played in the city's recovery from the severe typhoid epidemic linked to drinking polluted water in 1892. The idea that her city was the first in the country to use this type of filter system, and that the once polluted river water could be made safe to drink was "something very special to write about" (Barker, 1989, p. 5).

Narratives of shock and crisis, like those of the typhoid epidemic and strike, are often the ones that capture popular attention and are most accessible and quantifiable. However, well-functioning infrastructure, whether social or physical systems, that must co-evolve at the same scale as the economy to sustain functionality, are less visible (Seligson & McCants, 2021). Events that travel well in the popular imagination are more often dramatic ones, such as the shock of an epidemic, or perhaps a triumph for science in its recovery. Together with the widely told stories of mass industrialization, outbreaks of disease, migration, inequities, and unrest, in this city and others like it, this child's story of the water filter reminds us that there are also equally valid and important stories about those technologies that maintain stability, whether physical, organizational or both. The array of stories that we can find in the past can also spark imagination for a multiplicity of possible futures. Indeed, we can revisit our history anew, and along with it, envision new foundations for the future, "when we put into it technology that counts: not only the famous spectacular technologies but the low and ubiquitous ones" (Edgerton, 2007, p. 212).

THE ROLE OF HISTORICAL ANALYSIS IN SOCIALLY-DIRECTED SCIENCE AND TECHNOLOGY

Historical analysis of sociotechnical systems, a critical area of scholarship, holds great value as one component of socially-directed science and technology, that is, the intentional, holistic, and granular cross-disciplinary integration of the scientific and technological research and development processes with knowledge, concepts, and methodologies from humanistic fields and the social sciences towards more sustainable and equitable planetary and societal outcomes. A graphical representation of socially-directed science and technology, developed by the authors of this paper (Figure 3), has been employed in practice in both existing and new higher education institutions.[1]

When situated at the core of curriculum and pedagogy, socially-directed science and technology inquiry aims to create an integrative values-based intellectual foundation to guide agency and decision-making. Key characteristics include individual transformation and a focus on "principles of respect for life and human dignity, equal rights and social justice, respect for cultural diversity, and international solidarity and shared responsibility" (United Nations Educational, Scientific and Cultural Organization, 2015, p. 14) and styles of thought related to the interconnectedness, interdependence, complexity, and multidimensional nature of ecosystems (Haus der Kulturen der Welt & Max Planck Institute for the History of Science, 2020; United Nations Development Programme, 2020). Inclusion, equity, and social justice

1 Station1 is a nonprofit higher education institution based on socially-directed science and technology which is based in Lawrence, Massachusetts and was founded by the authors (Station1 Laboratory, Inc. Articles of Organization – General Laws, Chapter 180. Nonprofit corporation, Commonwealth of Massachusetts, United States, September 7th, 2016. Filing: 201696123530).

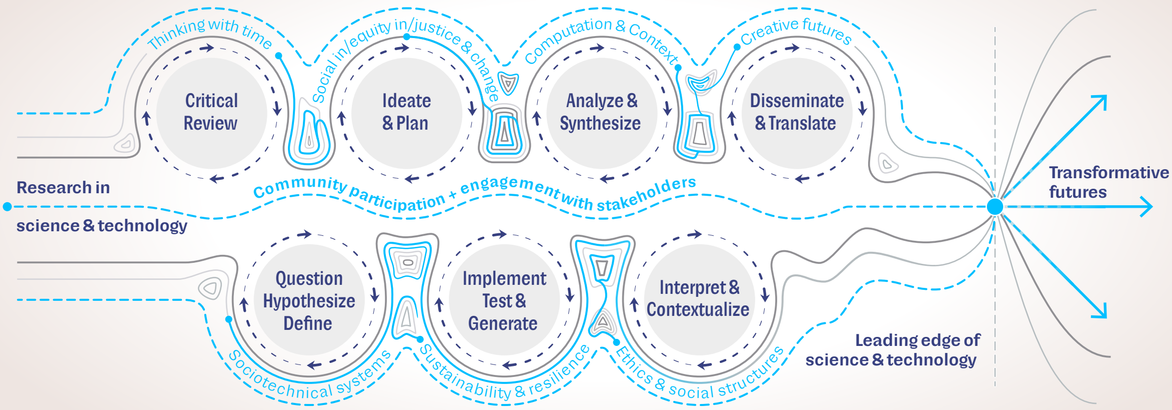

Figure 3: A graphical representation of socially-directed science and technology, developed by the authors of this paper, integrates scientific and technological research and development process components (gray circles) with knowledge, concepts, and methodologies from humanistic fields and the social sciences (cyan text on outside of circles) to influence and shape every stage of the process towards more sustainable and equitable planetary and societal outcomes. Historical analysis and thinking is integrated with topics from, for example, the social studies of science and technological systems (Biagioli, 1999; Felt et al., 2017), civic design, education, and engagement (Allen & Reich, 2013; Israel et al., 2012; McDowell, & Chinchilla, 2016; McDowell, 1996), feminism and gender studies (Cowan, 1983; Haraway, 1990; Lerman et al., 2003), racial in/justice (Crenshaw, 2017; Kendi, 2016; Slaton, 2010), environmental in/justice (Bullard, 1996; Thomas et al., 2013), sustainable development (United Nations Development Programme, 2020; United Nations Educational, Scientific and Cultural Organization, 2015, 2020), and ethical reasoning in social context (Herkert, 2005).

are weaved ubiquitously throughout pedagogy, research, and institutional cultures (Freire, 2014). This educational philosophy engages diverse bodies of scholarship and immersive experiences to bring the past, present, and future into conversation and seeks to achieve understanding which exceeds proximity of disciplines to trans-disciplinary synthesis and reflexive application of integrative knowledge throughout the entire research and development process, including at the earliest stages. Socially-directed science and technology reconciles the divergence of disciplinary norms in the formulation of integrative research questions that interrogate scientific and technological research and development decisions and potential downstream impacts within broader socioecological systems. In this context, it confronts one of the most foundational aspects of inquiry and the challenge of translation between scientific and technological disciplines, where research objectives often involve hypothesis, design, synthesis, quantification, simulation, etc. in pursuit of solutions, and humanistic fields and the social sciences where research questions may focus on the complexity of social systems, origins, and relationships between human and nonhuman actors, often with no definitive 'solution.' This type of transformation in science and technology education is imperative as one critical factor in the remediation of planetary damage and social inequities, as well as mitigating peril and maximizing the promise of emerging technologies.

Historical approaches, as integral components of socially-directed science and technology, encourages the formulation of questions, for example, related to origins, influences, and the linear assumptions of technological determinism (Smith & Marx, 1994); the reductive nature of popular narratives of progress and innovation (Vinsel & Russell, 2020; Wisnioski et al., 2019); hidden labor, maintenance, and expertise (Cowan, 1983; Stage & Vincenti, 1997); and the un/intended consequences of materials and design choices in technological systems (Knowles & Torero, 2020; Winner, 1986; Zimring, 2017). An emphasis on the temporal dimension highlights the pitfalls of short-term thinking and prompts students to imagine their trajectory as part of a longer planetary ecosystem. The integration of historical analysis is not intended to impose contemporary values onto the past, or to be prescriptive or predictive of 'solutions' for contemporary challenges. Rather, it serves to enable an understanding of the ambiguities, trade-offs, incentive structures, desired outcomes and unintended consequences, and relationships to in/equities within sociotechnical systems.

From the renovated textile mills[2] housing a burgeoning ecosystem of socially-directed science and technology, the former site of the LES is now invisible from afar; the test filters once meticulously cared for

2 The Wood Worsted Mill was built in 1912 in Lawrence, Massachusetts (U.S. National Register of Historic Places # 10000539) and is the current site of Station1 within the Riverwalk complex.

are reclaimed by overgrowth. What was once a wool sorting room is now a teaching and learning space bustling with the conversation of research rather than the clamor of machines. Teaching *with* the history of materials technology in Lawrence, embedded in the contemporary city, becomes more than an abstract case study. Exploring the maps, ledgers, photographs, and scientific publications of the LES at the Lawrence History Center, in the former headquarters of the Essex Company, whose mark can be seen in every part of the city, becomes an even more engaged process of reading. When walking around the city with the lens of history, materials, and equity, we make an intention to pause, to engage in 'slow-looking' (Tishman, 2018), to observe, to question. At the interface of water, brick, and iron of the canal system, we uncover hidden traces of technologies, social practices of design, construction, maintenance, regulation, and abandonment. This experiential learning serves to "connect us directly to the world we know rather than the strange world where technology lives" (Edgerton, 2007, p. xvii), and to engage more actively with a place. The combination of historical thinking, technology, and place also templates a deeper mindset for inquiry, unpacking assumptions about approaching the unfamiliar, whether in discipline, time, or culture. In the histories of the people in this place, whether scientists, engineers, industrialists, workers, or children, we seek to understand their actions, opportunities, and constraints. Within this historical frame, the approach to seeking out

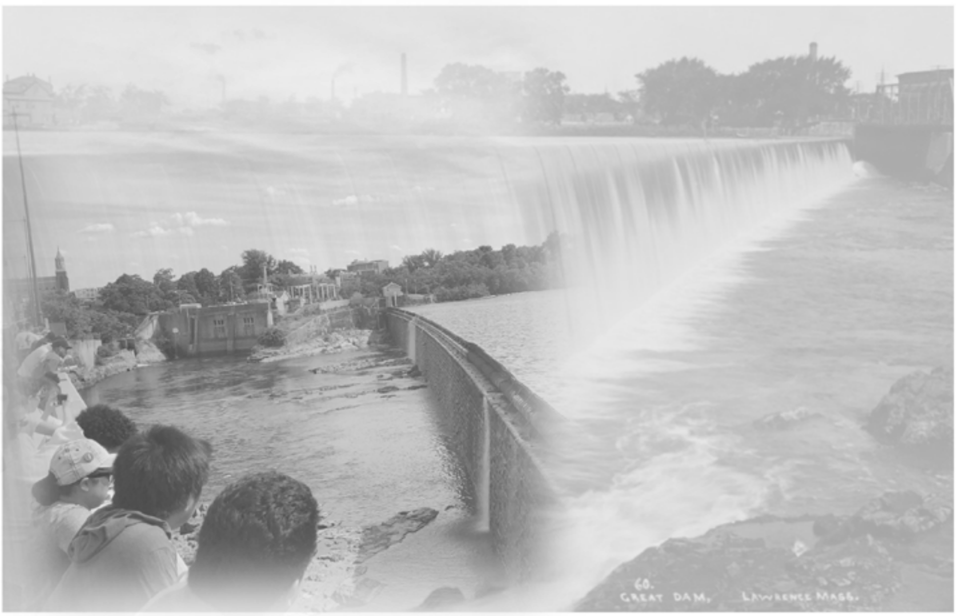

Figure 4: Lawrence Great Stone Dam, Lawrence. Source: Lawrence History Center, Accession 2003_012_001; and (left) Station1 Fellows visiting and learning about the Great Stone Dam in 2019 as part of the curriculum on socially-directed science and technology. Source: Station1, 2019.

stakeholders and making an effort to understand their context in any project becomes second nature. Learning embedded in the history of a place, whether uncovering hidden traces or exploring anew, translates into an approach to place in a generalizable way – to seek the unfamiliar in the local, and to seek connections to a human experience in the global.

CONCLUSIONS

This paper explores the dynamic social and material relationships across scales and connects the mechanisms and cumulative influence of material constituents within larger sociotechnical systems. When we think across scale with materials in mind, the connections between the often invisibly small, as well as the invisibly large, become clearer. We become attuned to the complex and non-linear relationships between structures at the microscale whose impact can be felt at the planetary scale. The concepts of technical landscapes were employed to understand the complex and continuous relationships between technologies related to water filtration across scales and their role in the shaping of place. Through this method, we may see a longer continuum between past, present, and future, within the heterogeneity of the surface of a grain of sand and the health of a city, or even a planet. "History can be an especially powerful tool in rethinking technology" (Edgerton, 2007, p. xvi), particularly when combined with materials. Indeed, sand is often a metaphor for deep time itself, a ubiquitous material with multiple narratives from the prosaic to the innovative, and much in-between. This critical constituent of 19th-century water infrastructure might even be considered to be hidden in the material infrastructure of the future technologies of digital models and simulations of contemporary water infrastructure systems, since silica, the precursor of silicon that sustains modern computing, is found in sand (Welland, 2010). By learning to uncover the often-hidden social structures of scientific and technological knowledge, materials, and infrastructures – to sit with the complexity, uncertainty, and often contradictions of the everyday world – can be a powerful bridge across disciplines and fields of practice. Embedded as a critical element in the model for inquiry-driven socially-directed science and technology, historical analysis and the mindset associated with thinking within a broader timescale can have a considerable impact on trajectories for contemporary practices and pedagogies of science and technology. D

The authors would like to thank Anne McCants for her insightful comments on the draft, the editorial team and anonymous reviewers for their attention and support in advancing the work of this paper, Katherine Zumach for her illustration expertise to aid in the visual translation of socially-directed science and technology framework, and the Lawrence History Center for their generosity in knowledge and archival material.

REFERENCES

Aerial and Panoramic Photographs. (Ca. 1850-1920). Glass Plate Negative and Photographs. Lawrence History Center – Immigrant City Archives and Museum, Lawrence, MA, United States.

ALLEN, D. S., & REICH, R. (Eds.). (2013). *Education, Justice, and Democracy*. The University of Chicago Press.

Allen Hazen Papers, 1883-1974 (MC 430). Massachusetts Institute of Technology, Department of Distinctive Collections.

BAILEY, H. H., & HAZEN, J. C. (1876). *Lawrence Massachusetts, 1876* [Map].

BARKER, M. (1989, May 15). *Marion Barker Oral History, The Strike of 1912* (Y. Erdener, Interviewer) [Interview]. Immigrant City Archives Oral History Collection.

BENSAUDE-VINCENT, B. (2016). Building Multidisciplinary Research Fields: The Cases of Materials Science, Nanotechnology and Synthetic Biology. In M. Merz & P. Sormani (Eds.), *The Local Configuration of New Research Fields: On Regional and National Diversity* (Vol. 29, pp. 45–60). Springer. https://doi.org/10.1007/978-3-319-22683-5_3

BIAGIOLI, M. (Ed.). (1999). *The Science Studies Reader*. Routledge.

BIJKER, W. E., HUGHES, T. P., & PINCH, T. (Eds.). (2012). *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology* (Anniversary ed.). MIT Press.

BINNIG, G., QUATE, C. F., & GERBER, CH. (1986). Atomic Force Microscope. *Physical Review Letters, 56*(9), 930–933. https://doi.org/10.1103/PhysRevLett.56.930

BRAY, F. (1997). *Technology and Gender: Fabrics of Power in Late Imperial China*. University of California Press.

BRAY, F. (2016). Flows and Matrices, Landscapes and Cultures. *Icon, 22*, 8–19.

BROWNING, A., ORTIZ, C., & BOYCE, M. C. (2013). Mechanics of Composite Elasmoid Fish Scale Assemblies and their Bioinspired Analogues. *Journal of the Mechanical Behavior of Biomedical Materials, 19*, 75–86. https://doi.org/10.1016/j.jmbbm.2012.11.003

BULLARD, R. D. (Ed.). (1996). *Unequal Protection: Environmental Justice and Communities of Color*. Sierra Club Books.

BURGESS, P. (1915). Mechanical Analyses of Sands. *Journal AWWA*, 2(3), 493–500. https://doi.org/10.1002/j.1551-8833.1915.tb14136.x

CAHN, M. (2005). Opera Omnia: The Production of Cultural Authority. In K. Chemla (Ed.), *History of Science, History of Text* (pp. 81–94). Springer. https://doi.org/10.1007/1-4020-2321-9_3

CLARK, H. W. (1907). *Eight Years' Work with Trickling Sewage Filters at the Lawrence Experiment Station*. Engineering News Publishing Company.

CLARK, H. W. (1909). *A Review of Twenty-one Years' Experiments upon the Purification of Sewage at the Lawrence Experiment Station*. Wright and Potter [reprint from Massachusetts Board of Health].

CLARK, H. W. (1927). An Outline of Sewage Purification Studies at the Lawrence Experiment Station. *Industrial & Engineering Chemistry, 19*(4), 448–452. https://doi.org/10.1021/ie50208a010

COEN, D. R. (2016). Big is a Thing of the Past: Climate Change and Methodology in the History of Ideas. *Journal of the History of Ideas, 77*(2), 305–321. https://doi.org/10.1353/jhi.2016.0019

COWAN, R. S. (1983). *More Work for Mother: The Ironies of Household Technology from the Open Hearth to the Microwave*. Basic Books.

CRENSHAW, K. (2017). *On Intersectionality: Essential Writings*. The New Press.

DASTON, L. (Ed.). (2004). *Things that Talk: Object Lessons from Art and Science*. Zone Books.

DE GENNES, P.-G. (1979). *Scaling Concepts in Polymer Physics*. Cornell University Press.

DE WOLF, C., HOXHA, E., HOLLBERG, A., FIVET, C., & OCHSENDORF, J. (2020). Database of Embodied Quantity Outputs: Lowering Material Impacts Through Engineering. *Journal of Architectural Engineering*, *26*(3), 04020016. https://doi.org/10.1061/(ASCE)AE.1943-5568.0000408

DORGAN, M. B. (1918). *Lawrence Yesterday and Today (1845-1918)*. http://magenweb.org/Essex/Lawrence/lawrenceindianhistory.html

DREICER, G. K. (2000). Building Myths: The "Evolution" from Wood to Iron in the Construction of Bridges and Nations. *Perspecta*, *31*, 130–140. https://doi.org/10.2307/1567265

DREICER, G. K. (2010). Building Bridges and Boundaries: The Lattice and the Tube, 1820–1860. *Technology and Culture*, *51*(1), 126–163. https://doi.org/10.1353/tech.0.0406

DREXLER, E. (1986). *Engines of Creation: The Coming Era of Nanotechnology*. Anchor.

EDDY, H. P. (1930). Massachusetts: The Cradle of Public-Health Engineering. *Sewage Works Journal*, *2*(3), 394–403.

EDGERTON, D. (2007). *The Shock of the Old: Technology and Global History since 1900*. Oxford University Press.

Engineering Records, Records of the Essex Company of Lawrence, Massachusetts, 1845-1987. Lawrence History Center – Immigrant City Archives and Museum, Lawrence, MA, United States.

ESTRIN, Y., BEYGELZIMER, Y., & KULAGIN, R. (2019). Design of Architectured Materials Based on Mechanically Driven Structural and Compositional Patterning. *Advanced Engineering Materials*, *21*(9), 1900487. https://doi.org/10.1002/adem.201900487

FELT, U., FOUCHE, R., MILLER, C. A., & SMITH-DOERR, L. (Eds.). (2017). *The Handbook of Science and Technology Studies*. MIT Press.

FEYNMAN, R. P. (1960). There's Plenty of Room at the Bottom. *Engineering and Science*, *23*(5), 22–36.

FINLAY, M. R. (2003). Old Efforts at New Uses: A Brief History of Chemurgy and the American Search for Biobased Materials. *Journal of Industrial Ecology*, *7*(3–4), 33–46. https://doi.org/10.1162/108819803323059389

FIVET, C., & BRÜTTING, J. (2020). Nothing is Lost, Nothing is Created, Everything is Reused: Structural Design for a Circular Economy. *The Structural Engineer*, *98*(1), 74–81.

FLEMINGS, M. C. (1986). Materials Science and Engineering. *Transactions of the Iron and Steel Institute of Japan*, *26*(2), 93–100. https://doi.org/10.2355/isijinternational1966.26.93

FLEMINGS, M. C. (1999). What Next for Departments of Materials Science and Engineering? *Annual Review of Materials Science*, *29*(1), 1–23. https://doi.org/10.1146/annurev.matsci.29.1.1

FORRANT, D. R., & GRABSKI, S. (2013). *Lawrence and the 1912 Bread and Roses Strike*. Arcadia.

FREIRE, P. (2014). *Pedagogy of the Oppressed* (30th Anniversary Edition). Bloomsbury.

FULLER, G. W. (1894, October 6). Sand Filtration of Water, with Special Reference to Results Obtained, at Lawrence, Massachusetts. *The Engineering Record*.

GOLDBLITH, S. A. (1995). *Of Microbes and Molecules: Food Technology, Nutrition, and Applied Biology at M.I.T., 1873-1988*. Food & Nutrition Press.

HANDLEY, S. (2000). *Nylon: The Story of a Fashion Revolution: A Celebration of Design from Art Silk to Nylon and Thinking Fibres*. Johns Hopkins University Press.

HANSEN, J. (2018). Shaping the Modern Body: Water Infrastructure in Los Angeles (1870–1920). *Body Politics, 6*(9), 47–70.

HARAWAY, D. (1990). *Simians, Cyborgs, and Women: The Reinvention of Nature*. Routledge.

HAUS DER KULTUREN DER WELT, & MAX PLANCK INSTITUTE FOR THE HISTORY OF SCIENCE. (2020). *Anthropocene Curriculum*. https://www.anthropocene-curriculum.org/

HAZEN, A. (1897). *Modern Methods of Supplying Cities with Pure Water*. Kalamazoo.

HAZEN, A. (1907). *Clean Water and How to Get it*. Wiley.

HAZEN, A. (1910). *The Filtration of Public Water-Supplies*. Wiley.

HEARN, M. (2014). *The History of the Essex Company*. Independent Publisher.

HERKERT, J. R. (2005). Ways of Thinking about and Teaching Ethical Problem Solving: Microethics and Macroethics in Engineering. *Science and Engineering Ethics, 11*(3), 373–385. https://doi.org/10.1007/s11948-005-0006-3

HOSLER, D. (1988). Ancient West Mexican Metallurgy: A Technological Chronology. *Journal of Field Archaeology, 15*(2), 191–217. https://doi.org/10.1179/009346988791974475

HUGHES, T. P. (1983). *Networks of Power: Electrification in Western Society, 1880-1930*. Johns Hopkins University Press.

ISRAEL, B. A., ENG, E., SCHULZ, A. J., & PARKER, E. A. (Eds.). (2012). *Methods in Community-Based Participatory Research for Health* (2nd Edition). Wiley.

JACKSON, J. B. (1984). *Discovering the Vernacular Landscape*. Yale University Press.

JAIN, A., ONG, S. P., HAUTIER, G., CHEN, W., RICHARDS, W. D., DACEK, S., CHOLIA, S., GUNTER, D., SKINNER, D., CEDER, G., & PERSSON, K. A. (2013). Commentary: The Materials Project: A Materials Genome Approach to Accelerating Materials Innovation. *APL Materials, 1*(1), 011002. https://doi.org/10.1063/1.4812323

KAMMEN, M. (2007). Photography and the Discipline of American Studies. *American Art, 21*(3), 13–18. https://doi.org/10.1086/526476

KEATING, A. D. (1994). *Invisible Networks: Exploring the History of Local Utilities and Public Works*. Krieger Publishing Company.

KENDI, I. X. (2016). *Stamped from the Beginning: The Definitive History of Racist Ideas in America*. Nation Books.

KNOWLES, S. G., & TORERO, J. (2020). Plyscrapers, Gluescrapers, and Mother Nature's Fingerprints. In A. E. Slaton (Ed.), *New Materials: Towards a History of Consistency* (pp. 151–174). Lever Press.

Lawrence City Atlases. (1875, 1888, 1906, 1926, 1938). Lawrence History Center – Immigrant City Archives and Museum, Lawrence, MA, United States.

Lawrence City Documents, Bound Annual Reports. (1846-1913). Lawrence History Center – Immigrant City Archives and Museum, Lawrence, MA, United States.

LAWRENCE HYDROELECTRIC PROJECT. (2020). *Lawrence Low Impact Hydropower Recertification Application* (FERC No 2800).

LECHTMAN, H. (1994). The Materials Science of Material Culture: Examples from the Andean Past. In D. A. Scott & P. Meyers (Eds.), *Archaeometry of Pre-Columbian Sites and Artifacts* (pp. 3–11). Getty Conservation Institute.

LERMAN, N., OLDENZIEL, R., & MOHUN, A. P. (2003). *Gender and Technology: A Reader*. Johns Hopkins University Press.

LI, Y., ORTIZ, C., & BOYCE, M. C. (2012). Bioinspired, Mechanical, Deterministic Fractal Model for Hierarchical Suture Joints. *Physical Review E, 85*(3), 031901. https://doi.org/10.1103/PhysRevE.85.031901

LIN, E., LI, Y., ORTIZ, C., & BOYCE, M. C. (2014). 3D Printed, Bio-Inspired Prototypes and Analytical Models for Structured Suture Interfaces with Geometrically-tuned Deformation and Failure Behavior. *Journal of the Mechanics and Physics of Solids, 73*, 166–182. https://doi.org/10.1016/j.jmps.2014.08.011

LINDQVIST, S. (2011). *Changes in the Technological Landscape: Essays in the History of Science and Technology*. Watson Publishing International LLC.

LINTSEN, H. W., HOLLESTELLE, M. J., & HÖLSGENS, H. N. M. (2017). *The Plastics Revolution: How the Netherlands Became a Global Player in Plastics*. Foundation for the History of Technology.

MALONE, P. M. (2009). *Waterpower in Lowell: Engineering and Industry in Nineteenth-century America*. Johns Hopkins University Press.

MARBLE, A. D. (1880). *Annual Report of the City Engineer of the City of Lawrence*. Printed at the Sentinel Office.

MARTIN-MARTINEZ, F. J., & BUEHLER, M. J. (2020). Multiscale Modeling of Structural Materials: Chemistry and Mechanical Performance. In W. Andreoni & S. Yip (Eds.), *Handbook of Materials Modeling: Applications: Current and Emerging Materials* (pp. 1541–1546). Springer. https://doi.org/10.1007/978-3-319-44680-6_81

Massachusetts Institute of Technology. Office of the President. Reports to the President, 1871-1930 (AC-0597). Massachusetts Institute of Technology. Libraries. Department of Distinctive Collections.

MASSACHUSETTS STATE BOARD OF HEALTH. (1887). *Annual Report of the State Board of Health of Massachusetts.* State Board of Health of Massachusetts.

MASSACHUSETTS STATE BOARD OF HEALTH. (1893). *A Guide to its Exhibit at the World's Columbian Exposition. 1893*. The Board.

MAYNARD, P. (1997). *The Engine of Visualization: Thinking through Photography*. Cornell University Press.

MCDOWELL, C. (1996). Democratic Education: Imagery, Language, and Culture. *International Journal of Social Education, 11*(1), 91–97.

MCDOWELL, C., & CHINCHILLA, M. Y. (2016). Partnering with Communities and Institutions. In E. Gordon & P. Mihailidis (Eds.), *Civic Media: Technology, Design, Practice* (pp. 461–480). https://doi.org/10.7551/mitpress/9970.003.0037

MELOSI, M. V. (2000). *The Sanitary City: Urban Infrastructure in America from Colonial Times to the Present*. University of Pittsburgh Press.

MILLS, H. (1893). Water Filtration in America. *Engineering News, 97*.

MILLS, H. F. (1912). *Mills, Hiram Francis, 1912-1921* (AC 0013, Box 13, Folder 403). Massachusetts Institute of Technology. Libraries. Department of Distinctive Collections.

MIT OFFICE OF THE PRESIDENT. (1916). *Reports of the President and Treasurer*. Massachusetts Institute of Technology.

MODY, C. C. M. (2011). *Instrumental Community: Probe Microscopy and the Path to Nanotechnology*. MIT Press.

MOLLOY, P. M. (1980). Nineteenth-century Hydropower: Design and Construction of Lawrence Dam, 1845-1848. *Winterthur Portfolio, 15*(4), 315–343. https://doi.org/10.1086/495980

NDIAYE, P. A. (2007). *Nylon and Bombs: DuPont and the March of Modern America*. Johns Hopkins University Press.

NYE, D. E. (1994). *American Technological Sublime*. MIT Press.

NYE, D. E. (Ed.). (1999). *Technologies of Landscape: From Reaping to Recycling*. University of Massachusetts Press.

Oldenziel, R., & Trischler, H. (2016). *Cycling and Recycling: Histories of Sustainable Practices*. Berghahn.

Ortiz, C., & Boyce, M. C. (2008). Bioinspired Structural Materials. *Science, 319*(5866), 1053–1054. https://doi.org/10.1126/science.1154295

Oxman, N. (2010). Structuring Materiality: Design Fabrication of Heterogeneous Materials. *Architectural Design, 80*(4), 78–85. https://doi.org/10.1002/ad.1110

Oxman, N., Ortiz, C., Gramazio, F., & Kohler, M. (2015). Material Ecology. *Computer-Aided Design, 60*, 1–2. https://doi.org/10.1016/j.cad.2014.05.009

Perkins, T. T., Smith, D. E., & Chu, S. (1994). Direct Observation of Tube-like Motion of a Single Polymer Chain. *Science, 264*(5160), 819–822. https://doi.org/10.1126/science.8171335

Photographs of Water Filtration System Under Construction. (Ca. 1893-1910). Lawrence History Center – Immigrant City Archives and Museum, Lawrence, MA, United States.

Rowell, W. E. (1912). Introduction. In F. B. Sanborn, R. E. Todd, F. H. McLean, & White Fund, *The Report of the Lawrence Survey; Studies in Relation to Lawrence, Massachusetts, Made in 1911* (pp. 15–17). The Andover Press.

Sedgwick, W. T. (1906). The Experimental Method in Sanitary Science and Sanitary Administration. *Science, 23*(584), 362–367. https://doi.org/10.1126/science.23.584.362

Sedgwick, W. T. (1922). *Principles of Sanitary Science and the Public Health with Special Reference to the Causation and Prevention of Infectious Diseases*. Macmillan.

Seewang, L. (2019). Salubrious Berlin: Public Streets and Universal Bodies of the Modern Municipality, 1860–1909. In A. Kockelkorn & N. Zschocke (Eds.), *Productive Universals-Specific Situations: Critical Engagements in Art, Architecture, and Urbanism* (pp. 127–159). Sternberg.

Seligson, D., & McCants, A. E. C. (2021). Coevolving Institutions and the Paradox of Informal Constraints. *Journal of Institutional Economics*, [First View], 1–20. https://doi.org/10.1017/S1744137420000600

Slaton, A. E. (2001). *Reinforced Concrete and the Modernization of American Building, 1900-1930*. Johns Hopkins University Press.

Slaton, A. E. (2010). *Race, Rigor, and Selectivity in U.S. Engineering: The History of an Occupational Color Line*. Harvard University Press.

Slaton, A. E. (2020). *New Materials: Towards a History of Consistency*. Lever Press. https://doi.org/10.1353/book.78801

Smith, F. M. (1947). *The Essex company on the Merrimack at Lawrence*. Newcomen Society of England, American Branch.

Smith, M. R., & Marx, L. (Eds.). (1994). *Does Technology Drive History? The Dilemma of Technological Determinism*. MIT Press.

Spero, E. F. (2013). The Tua River Valley: A Technological Landscape. In A. McCants, E. Beira, J. M. Lopes Cordeiro, & P. B. Lourenço (Eds.), *Railroads in Historical Context: Construction, Costs and Consequences: Vol. III* (pp. 239–248). Foz Tua.

Spero, E. F., & Pereira, H. S. (2016). The Tua Valley in Transition, Symbol and Technological Landscape. *CEM Cultura, Espaço & Memória, 7*, 223–241.

Stage, S., & Vincenti, V. B. (1997). *Rethinking Home Economics: Women and the History of a Profession*. Cornell University Press.

Stewart-Smith, D. (1999). *The Pennacook Indians and the New England Frontier, Circa 1604-1733*. The Union Institute.

Strober, M. (2011). *Interdisciplinary Conversations: Challenging Habits of Thought*. Stanford University Press.

THOMAS, D. S. K., PHILLIPS, B. D., LOVEKAMP, W. E., & FOTHERGILL, A. (Eds.). (2013). *Social Vulnerability to Disasters*. CRC Press.

THORSHEIM, P. (2016). *Waste into Weapons: Recycling in Britain during the Second World War*. Cambridge University Press.

TISHMAN, S. (2018). *Slow Looking: The Art and Practice of Learning Through Observation*. Routledge.

ULM, F.-J., VANDAMME, M., BOBKO, C., ORTEGA, J. A., TAI, K., & ORTIZ, C. (2007). Statistical Indentation Techniques for Hydrated Nanocomposites: Concrete, Bone, and Shale. *Journal of the American Ceramic Society, 90*(9), 2677–2692. https://doi.org/10.1111/j.1551-2916.2007.02012.x

UNITED NATIONS DEVELOPMENT PROGRAMME. (2020). *Human Development Report 2020: The Next Frontier: Human Development and the Anthropocene* [Human Development Reports]. UNDP. http://hdr.undp.org/en/content/human-development-report-2020

UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION. (2015). *Rethinking Education: Towards a Global Common Good?* UNESCO. https://unesdoc.unesco.org/ark:/48223/pf0000232555

UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION. (2020). *Education for Sustainable Development: A Roadmap*. UNESCO. https://unesdoc.unesco.org/ark:/48223/pf0000374802?posInSet=1&queryId=73dbbf8d-800c-49e1-b293-24f28e7bcf45

VAN ANDERS, G., KLOTSA, D., KARAS, A. S., DODD, P. M., & GLOTZER, S. C. (2015). Digital Alchemy for Materials Design: Colloids and Beyond. *ACS Nano, 9*(10), 9542–9553. https://doi.org/10.1021/acsnano.5b04181

VINSEL, L., & RUSSELL, A. L. (2020). *The Innovation Delusion: How Our Obsession with the New Has Disrupted the Work That Matters Most*. Penguin Random House.

VISELTEAR, A. J. (1988). The Emergence of Pioneering Public Health Education Programs in the United States. *The Yale Journal of Biology and Medicine, 61*(6), 519–548.

WATSON, B. (2005). *Bread and Roses: Mills, Migrants, and the Struggle for the American Dream*. Penguin.

WEISS, S. (2020). Making Engineering Visible: Photography and the Politics of Drinking Water in Modern Paris. *Technology and Culture, 61*(3), 739–771. https://doi.org/10.1353/tech.2020.0072

WELLAND, M. (2010). *Sand: The Never-Ending Story*. University of California Press.

William T. Sedgwick Correspondence, 1893-1908 (MC 444, Box C). Massachusetts Institute of Technology, Department of Distinctive Collections.

WINNER, L. (1986). *The Whale and the Reactor: A Search for Limits in an Age of High Technology*. The University of Chicago Press.

WINSLOW, C.-E. A. (1953). There Were Giants in Those Days. *American Journal of Public Health and the Nations Health, 43*(6 Pt 2), 15–19. https://doi.org/10.2105/ajph.43.6_pt_2.15

WISNIOSKI, M., HINTZ, E. S., & KLEINE, M. S. (Eds.). (2019). *Does America Need More Innovators?* MIT Press.

YANG, A., & DASTON, L. (2017, April 1). *Time (and Time Again). Temporality, Criticality, and the Historical Imagination: A Conversation with Historian of Science Lorraine Daston* [Deep Time Chicago Pamphlet Series]. Anthropocene Curriculum. https://www.anthropocene-curriculum.org/contribution/time-and-time-again

ZIMRING, C. A. (2005). *Cash for Your Trash: Scrap Recycling in America*. Rutgers University Press.

Zimring, C. A. (2017). *Aluminum Upcycled: Sustainable Design in Historical Perspective*. Johns Hopkins University Press.