

**Visible Hands and Invisible Standards:
The Nuts and Bolts of the Second Industrial Revolution**

Stephen Mihm, University of Georgia

Economic History Seminar

Yale University

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Is the “new” history of capitalism all that new? ¹ Business historians and economic historians who have toiled away for decades are likely to answer in the negative. And for good reason: much of the scholarship that parades under the history of capitalism banner seems, with some subtle differences, to resemble the work done by an earlier generation of scholars. A cynic could be forgiven for thinking that the only significant difference between the new and old scholarship is that the mainstream historical profession now seems to agree that studying corporations, finance, and capitalists is now cutting edge, and thus worthy of widespread recognition in the form of awards, tenure-track jobs, and other professional accolades.

There is reason to be skeptical. In the spirit of that skepticism, I wish to engage with that older literature, as well as the very real criticisms that have been leveled at it by succeeding generations of business and economic historians. And I wish to propose another way – though by no means the only way – of understanding the critical developments of nineteenth century capitalism that moves beyond both the traditional preoccupation with the firm as the preferred unit of analysis and the belief that the “managerial revolution” as the defining development of the second industrial revolution. Whether this constitutes anything particularly “new” is something that I will leave to the reader to decide.

In so much of the literature in traditional business history, the twin focus on the firm and on management very much originated in the work of Alfred D. Chandler, Jr.. In his signal works – *Strategy and Structure*, *The Visible Hand*, *Scale and Scope* – Chandler framed the story of modern capitalism as a triumph of organization.² In sometimes excruciating detail, Chandler

¹ For meditations on this question, see Sven Beckert, “History of American Capitalism,” in Eric Foner and Lisa McGirr, eds., *American History Now* (Philadelphia: Temple University Press, 2011), 314-335; Louis Hyman, “Why Write the History of Capitalism?” *Symposium Magazine*, 8 July 2013.

² Alfred D. Chandler, Jr., *Strategy and Structure: Chapters in the History of Industrial Enterprise* (Cambridge, Mass.: Harvard University Press, 1962); *The Visible Hand: The Managerial Revolution in American Business* (Cambridge, Mass.: Harvard University Press, 1977); *Scale and Scope: The Dynamics of Industrial Capitalism* (Cambridge, Mass.: Harvard University Press, 1990).

chronicled the way that traditional business enterprises coordinated by market forces came to be overshadowed by sprawling corporate bureaucracies administered by untold numbers of salaried managers. While the individual entrepreneur making his way in the market did not entirely disappear in Chandler's narrative, he emphatically believed that "the managerial revolution" was the real story of modern capitalism.

These managers, Chandler argued, took over the "coordination and integration of the flow of goods and services from the production of the raw materials through the several processes of production to the sale to the ultimate consumer." Not coincidentally, these same managers often presided over the creation of vast industrial enterprises characterized by both vertical and horizontal integration. The resulting "managerial hierarchies" proved more effective than markets in allocating goods and resources. In the process, "the visible hand of management replaced the invisible hand of market forces where and when new technology and expanded markets permitted a historically unprecedented high volume and speed of materials through the processes of production and distribution."³

Chandler's preoccupation with the rise of modern management owed much to his exposure to Talcott Parsons, and by extension, Max Weber. Like Robert Wiebe, whose landmark *The Search for Order* told a parallel story, Chandler put bureaucratic rationality and large-scale organizations at the center of his narrative.⁴ The historian Louis Galambos dubbed the work of

³ Chandler, *Visible Hand*, 12. On Chandler's body of work, and its enduring influence, see Thomas K. McCraw, "The Intellectual Odyssey of Alfred D. Chandler, J.," in McCraw, ed., *The Essential Alfred Chandler: Essays Toward a Historical Theory of Big Business* (Boston: Harvard Business School Press, 1988); Charles S. Maier, "Accounting for the Achievements of Capitalism: Alfred Chandler's Business History," *Journal of Modern History* 65 (December 1993), 771-782; Richard R. John, "Elaborations, Revisions, Dissents: Alfred D. Chandler, Jr.'s, 'The Visible Hand' after Twenty Years," *Business History Review* 71 (Summer 1997), 151-200; Steve Usselman, "Still Visible: Alfred D. Chandler's *The Visible Hand*," *Technology and Culture* 47 (July 2006), 584-596; Thomas K. McCraw, "Alfred Chandler: His Vision and Achievement," *Business History Review* 82 (Summer 2008), 207-226.

⁴ Robert H. Wiebe, *The Search for Order, 1877-1920*. New York: Hill and Wang, 1967. On Wiebe's comparable influence, as well as a sustained critique of work in this vein, see Kenneth Cmiel, "Destiny and Amnesia: The Vision of Modernity in Robert Wiebe's *The Search for Order*," *Reviews in American History* 21 (1993), 352-368.

Chandler, Wiebe, and others part of a new “organizational synthesis,” which offered a new way of understanding the sweeping economic changes of the late nineteenth and early twentieth centuries. In the work of Chandler, Wiebe, and others, “formal, hierarchical structures of authority” came to dominate the nation. “America’s rendezvous,” wrote Galambos, “was not with the liberal’s good society. It was with bureaucracy.”⁵

By the 1980s, the organizational synthesis was less the cutting edge than a foil for the ascendant field of social history. Disciples of history “from the bottom up” had little patience for Chandler’s blithe disregard of labor, much less his seemingly celebratory account of big business – though this dismissal, as Richard John has argued, overlooked much that was progressive in Chandler’s writings. Likewise, the cultural historians who succeeded them had no interest in Chandler’s work, which largely disregarded the power of ideas. For these reasons, Chandler’s work had limited resonance inside the mainstream historical profession, even if crude simplifications of his arguments soon surfaced in history textbooks.⁶

But Chandler was hardly ignored and forgotten among those who studied the history of capitalism before it went by that name. In business history, never mind several allied disciplines, Chandler attracted a number of adherents, many of whom produced works that echoed and elaborated points he had first articulated. His students and colleagues and collaborators, particularly at Harvard Business School, produced a range of work that can fairly be described as “Chandlerian” in its approach to the history of modern business enterprise. Works by Thomas

⁵ Galambos has written three separate pieces assessing the organizational synthesis. See “The Emerging Organizational Synthesis in Modern American History,” *Business History Review* 44 (Autumn 1970), 279-290; “Technology, Political Economy, and Professionalization: Central Themes of the Organizational Synthesis,” *Business History Review* 57 (Winter 1983), 471-493; “Recasting the Organizational Synthesis: Structure and Process in the Twentieth and Twenty-First Centuries,” *Business History Review* 79 (Spring 2005), 1-38.

⁶ Richard R. John, “Turner, Beard, Chandler: Progressive Historians,” *Business History Review* 82 (Summer 2008), 227-240; John, “Elaborations, Revisions, Dissents,” 174, n. 72.

McCraw and Richard Tedlow are typical of a historiographical tradition that built upon, rather than challenged, Chandler's ideas.⁷

So, too, did works by scholars who challenged or revised Chandler's findings. Scholars like Thomas Cochran sought – largely unsuccessfully – to argue that the more critical phase came earlier, before large, hierarchical corporations populated the economic landscape. Still others, like Philip Scranton, assailed Chandler for exaggerating the importance of the bureaucratic corporations of the late nineteenth century, highlighting instead the continuing vitality of smaller firms in the late nineteenth and early twentieth centuries. Sociologist Neil Fligstein argued that the rise of large, bureaucratic corporations had little to do with efficiency and everything to do with attempts to control competition. Still others have raised questions about the contemporary relevance of Chandler's model, given the degree to which bureaucratic firms have become increasingly obsolete and inefficient since the 1970s. The economist Richard Langlois, for example, has argued that the large bureaucratic organizations hailed by Chandler were but a temporary expedient, a product of an “imbalance” between new technologies and old markets.⁸

Other scholars have expressed skepticism as to whether the corporate bureaucracies were all that rational or efficient. If Chandler viewed the managerial revolution from a high altitude, historians like Walter Licht examined their operation on the ground, finding plenty of human conflict, infighting, face-to-face negotiation, and other behavior supposedly banished by the

⁷ See, e.g., Thomas K. McCraw, *Prophets of Regulation: Charles Francis Adams, Louis D. Brandeis, James M. Landis, Alfred E. Kahn* (Cambridge, Mass.: Harvard University Press, 1984); Richard S. Tedlow, *New and Improved: The Story of Mass Marketing in America* (New York: Basic Books, 1990); Tony A. Freyer, *Regulating Big Business: Antitrust in Great Britain and America, 1880-1990* (New York: Cambridge University Press, 1992).

⁸ Philip Scranton, “Diversity in Diversity: Flexible Production and American Industrialization, 1880-1930,” *Business History Review* 65 (Spring 1991), 27-90; Philip Scranton, *Endless Novelty: Specialty Production and American Industrialization, 1865-1925* (Princeton, New Jersey: Princeton University Press, 1997); Richard M. Langlois, “The Vanishing Hand: The Changing Dynamics of Industrial Capitalism,” *Industrial and Corporate Change* 12 (2003), 351-385.

managerial revolution. This idea – that hierarchical firms rarely function as smoothly or efficiently as Chandler imagined – received its most sustained treatment in Richard White’s recent *Railroaded: The Transcontinentals and the Making of Modern America*. At least in the case of these especially inept enterprises, White found little evidence that they acted as “harbingers of order, rationality, and effective large-scale organization.” They were, he concluded, little more than a band of “inefficiently, costly, dysfunctional corporations.”⁹

Most of these criticisms have merit, but they tend to simultaneously replicate a number of biases inherent in Chandler’s work. For example, most skeptics of Chandler tend to retain the firm – whether large or small, hierarchical or flat, efficient or inept – as the primary unit of analysis. Moreover, a good number of Chandler’s critics tend to retain the focus on bureaucracy that was so central to the organizational synthesis. These scholars may not be “children of Max Weber,” as Richard White aptly described Chandler and Wiebe. Nor are the bureaucracies they study necessarily rational or efficient. But by remaining wedded to an intellectual tradition that made bureaucratic rationality the *sine qua non* of modernity, these historians remain prisons of the original organizational synthesis.¹⁰

Those scholars who broke decisively with Chandler’s focus on large, bureaucratic corporations have sought to reinstate markets to their privileged position within the history of American capitalism. While much of this scholarship, particularly the work of Philip Scranton, was a useful corrective, it runs of the risk of overlooking other “coordinating mechanisms” that occupy fall “beyond markets and hierarchies,” to use the felicitous phrasing of Naomi Lamoreaux and her collaborators. In an influential article published in the *American Historical*

⁹ Walter Licht, *Working for the Railroad: The Organization of Work in the Nineteenth Century* (Princeton, New Jersey: Princeton University Press, 1983); Richard White, *Railroaded: The Transcontinentals and the Making of Modern America* (New York: W. W. Norton, 2011), xxix, xxvi.

¹⁰ White, *Railroaded*, xxx.

Review, Lamoreaux, Daniel Raff, and Peter Temin sought to subsume Chandler's ideas within a far more expansive – and far less teleological – framework for understanding the evolution of the capitalist economy. In particular, they sought to push historians and economists to recognize the role of “long-term relationships” as a means of addressing problems with coordination and imperfect information.¹¹

This was long overdue. But this was not, obviously, the last word on the subject. In the spirit of Lamoreaux's proposal, I want to suggest yet another way of understanding the monumental economic changes of the late nineteenth and early twentieth centuries. This means contemplating some unappreciated, often invisible means of coordinating economic activity. The mechanisms I have in mind relied on a very different set of social relations than competition (markets) and commands (hierarchies). They depended instead on cooperation, though they invariably engendered intense conflict between different classes and interest groups battling for supremacy in the second industrial revolution.

The development that I wish to put forward today can be summarized in one word: standardization. This idea, which in most basic form simply means “making things the same,” is an elusive, but extraordinarily important part of the story that Chandler and his critics have identified, even if it largely missing from existing accounts of the second industrial revolution. Standardization is rarely, if ever, the work of a single organization, even if a standard may initially originate within an individual firm, trade association, or other specific, circumscribed location. Rather, standardization, by one definition, is “a process of constructing uniformities across time and space, through the generation of agreed-upon rules.” This process, which is

¹¹ Naomi R. Lamoreaux, Daniel M. G. Raff, and Peter Temin, “Beyond Markets and Hierarchies: Toward a New Synthesis in American Business History,” *American Historical Review* 108 (April 2003), 404-433. See also Naomi R. Lamoreaux and Daniel M. G. Raff, eds., *Coordination and Information: Historical Perspectives on the Organization of Enterprise* (Chicago: University of Chicago Press, 1995) and Naomi R. Lamoreaux, Daniel M. G. Raff, and Peter Temin, “Against Whig History,” *Enterprise & Society* 5 (September 2004), 376-387.

inherently social, can be conceived as “the meeting of numerous parties with the aim of obtaining legitimate coordination, comparability, and compatibility across contexts.”¹²

This kind of uniformity should not be confused with the internal standards of a single firm or business. Take, for example, the system of interchangeable parts that the French developed in the late eighteenth century, and the Americans commercialized in the nineteenth century. In this system – dubbed the “American system – a firm that builds guns using standard parts: if one part breaks, an identical part can be substituted. This is an internal standard that is peculiar to a single firm. But the part may not work on another manufacturer’s guns, because that other manufacturer is likely using an entirely different set of interchangeable parts. The internal standard divides as much it unifies. By contrast, the standardization as defined here is a process by which “sameness” – uniformity” – connects disparate localities, communities, corporations, markets, and states across space and time.¹³

Standardization can encompass a wide range of coordinating mechanisms. These include uniform accounting standards; metrological standards governing units of measurement; technical standards defining a uniform industrial component; and quality standards that define various commodities. Such standards, more often than not, gain currency via cooperation, not competition. They are born out of trade associations, scientific bodies, professional associations, congresses, and other venues that transcended individual firms. While they help make markets, they are rarely perfect, even if they solve many problems associated with “asymmetric

¹² Stefan Timmermans and Steven Epstein, “A World of Standards but not a Standard World: Toward a Sociology of Standards and Standardization,” *Annual Review of Sociology* 36 (2010), 69-89. For representative works on the sociology of standards, see James Sumner and Graeme J. N. Gooday, “Introduction,” *History of Technology* 28 (2008), 1-14; Martha Lampland and Susan Leigh Star, *Standards and Their Stories: How Quantifying, Classifying, and Formalizing Practices Shape Everyday Life* (Ithaca, New York: Cornell University Press, 2009); Lawrence Busch, *Standards: Recipes for Reality* (Cambridge, Mass.: MIT Press, 2011).

¹³ Ken Alder, *Engineering the Revolution: Arms & Enlightenment in France, 1763-1815* (Chicago: University of Chicago Press, 1997); David A. Hounshell, *From the American System to Mass Production, 1800-1932: The Development of Manufacturing Technology in the United States* (Baltimore: Johns Hopkins University Press, 1984).

information” that have historically vexed relationships between manufacturers, suppliers, and distributors.¹⁴

There is (and was) a paradoxical quality to this process. After all, all standards are born of local contexts and are initially peculiar to a single, bounded community. This is true of the inch as it is of the meter, and true of technical standards, from railroad gauge to the uniform system of screw threads that I will discuss shortly. The challenge, then, that any historian of standards faces is to document how *a* standard becomes *the* standard: how, in other words, it moves from something particular to something that has some claim to universality, even if that claim is contested and contingent.

This process does not, for the most part, take place within the firms and hierarchies beloved by Chandler. Rather, it is in the cumulative acts of adoption within a community or network that invest standards with power as coordinating mechanisms. This concept, which legal theorist David Singh Grewal has dubbed “network power,” makes possible a recognition that the astonishing logistical and administrative challenges generated by the second industrial revolution required much more than cadres of middle managers capable of coordinating the

¹⁴ There is a small but growing literature on the economics of standards. The best known works relate to the so-called “path dependence” literature. See, for example, Paul A. David, “Clio and the Economics of QWERTY,” *American Economic Review* 75 (1985), 332-337 and “Why Are Institutions the ‘Carriers of History’?: Path Dependence and the Evolution of Conventions, Organizations, and Institutions,” *Structural Change and Economic Dynamics* 5 (1994), 205-220, as well as the essays in Pierre Garrouste and Stavros Ioannides, eds., *Evolution and Path Dependence in Economic Ideas: Past and Present* (Northampton, Mass.: Edward Elgar, 2001). But there is also a robust literature in economics on standards and kindred subjects that provides more direct insights into the ways that standards can function as coordinating mechanisms. See, e.g., Yoram Barzel, “Measurement Cost and the Organization of Markets,” *Journal of Law and Economics* 25 (1982), 27-48; Charles Kindleberger, “Standards as Public, Collective, and Private Goods,” *Kyklos* 36 (1983), 377-396; Sanford V. Berg, “The Production of Compatibility: Technical Standards as Collective Goods,” *Kyklos* 42 (1989), 361-383; David A. Paul and Shane Greenstein, “The Economics of Compatibility Standards: An Introduction to Recent Research,” *Economics of Innovation and New Technology* 1 (1990), 3-41; Christiano Antonelli, “Localized Technological Change and the Evolution of Standards as Economic Institutions,” *Information Economics and Policy* 6 (1994), 195-216; Lawrence Busch, “The Moral Economy of Grades and Standards,” *Journal of Rural Studies* 16 (2000), 273-283; Olivier Fabereau, Olivier Biencourt, and François Eymard-Duvernay, “Where Do Markets Come From? From (Quality) Conventions!” in Olivier Favereau and Emmanuel Lazega, eds., *Conventions and Structures in Economic Organization: Markets, Hierarchies, and Networks* (Northampton, Mass.: Edward Elgar, 2001), 213-252; Yoram Barzel, “Standards and the Form of Agreement,” *Economic Inquiry* 42 (2004), 1-13.

movement of goods and services. Standardization required the collaboration of managers, engineers, scientific bodies, professional associations, and entrepreneurs from firms large and small. It was a collective undertaking that, frankly, dwarfed the logistical and operational challenges faced by individual firms. While it is now inextricably entwined with globalization, standardization in the nineteenth century was something that took place within national borders.¹⁵

Given Chandler's obsessive focus on the firm, it perhaps understandable why he dedicated but a few pages to standardization in *The Visible Hand*. But he was hardly alone in relegating standardization to playing a minor role: many works in business history and the history of technology that cover the late nineteenth and twentieth century barely mention campaigns for standardization. Only a few scholars over the past few decades – David Noble and Steve Usselman, most notably -- have acknowledged the centrality of standards and standardization; a few others have taken up individual campaigns for standardization of track gauge, for example, but these narrower works do little to establish a larger explanatory framework in which standardization takes a central place.¹⁶

¹⁵ David Singh Grewal, *Network Power: The Social Dynamics of Globalization* (New Haven: Yale University Press, 2008). See also Alessandra Casella, "Product Standards and International Trade: Harmonization through Private Coalitions," *Kyklos* 54 (2001), 243-264; Winton Higgins and Tamm Hallström, "Standardization, Globalization, and Rationalities of Government," *Organization* 14 (2007), 685-704; Allison Loconto and Lawrence Busch, "Standards, Techno-Economic Networks, and Playing Fields: Performing the Global Market Economy," *Review of International Political Economy* 17 (August 2010), 507-536; Tim Büthe and Walter Mattli, "International Standards and Standard-Setting Bodies," in David Coen, Graham Wilson, and Wyn Grant, eds., *Oxford Handbook on Business and Government* (New York: Oxford University Press, 2010), 440-471; Nils Brunsson, Andreas Rasche, and David Seidl, "The Dynamics of Standardization: Three Perspectives on Standards in Organizational Studies," *Organization Studies* 33 (2012), 613-632.

¹⁶ David F. Noble, *America By Design: Science, Technology, and the Rise of Corporate Capitalism* (New York: Oxford University Press, 1977), 69-83; Steven W. Usselman, *Regulating Railroad Innovation: Business, Technology, and Politics in America, 1840-1920* (New York: Cambridge University Press, 2002), 231-241, 359-367; Douglas J. Puffert, *Tracks across Continents, Paths through History: The Economic Dynamics of Standardization in Railway Gauge* (Chicago: University of Chicago Press, 2009). Recently, Philip Scranton and Patrick Fridenson cited standards and standardization as one of the areas that business historians might profitably study. See Scranton and Fridenson, *Reimagining Business History* (Baltimore: Johns Hopkins University Press, 2013), 160-165.

It is easy, of course, to overlook standards and standardization. As one sociologist has ruefully observed, “standards and standardization are such widespread and omnipresent features of modernity that, ironically, their precise...significance stands at risk of vanishing out of sight.” This combination of ubiquity and banality is, of course, one reason they are both exceedingly powerful and simultaneously invisible. As another theorist of standards and standardization has noted, “successful standards, if they are noticed at all, simply appear as authoritative, objective, uncontroversial, and natural. In short, they are “recipes for reality.” But like most recipes, they recede from memory once the finished project is in hand. Little wonder they have received so little attention in historical circles.¹⁷

That is now beginning to change, thanks to the work of Craig Murphy and JoAnne Yates as well as Andrew Russell, whose book on the historical origins of “open standards” examines these efforts to craft industry-wide standards beginning in the late nineteenth century. “By defining standards,” writes Russell, organizations dedicated to setting standards “facilitated the existence of multiple sources of supply and thus provided a means for small- and medium-sized industrial firms to avoid the specter of monopoly.” They were, in other words, a powerful means of coordinating economic activity without resorting to the need for the hierarchical organization of large firms integrated along vertical and horizontal lines.¹⁸

But this does not mean that standards had no relevance for Chandlerian firms. Many of these corporations, particularly those born in the merge and acquisition wave of the late nineteenth and early twentieth centuries, consisted of numerous formerly independent firms that

¹⁷ Timmermans and Epstein, “A World of Standards but Not a Standard World,” 84; Andrew L. Russell, *Open Standards and the Digital Age: History, Ideology, and Networks* (New York: Cambridge University Press, 2014), 16.

¹⁸ Craig N. Murphy and JoAnne Yates, “Charles Le Maistres: Entrepreneur in International Standardization,” *Enterprises et Histoire* 51 (June 2008), 10-27; Craig N. Murphy and JoAnne Yates, *The International Organization for Standardization (ISO): Global Governance through Voluntary Consensus* (New York: Routledge, 2009); Russell, *Open Standards*, 26.

were forcibly consolidated under a single set of upper managers. The phrasing used by Richard White to describe the transcontinentals – “giant corporations employing thousands of men [that] were less tightly centralized organizations than collections of fiefdoms” – accurately describes any number of the large, horizontally and vertically integrated behemoths of the era. These amalgamations had to operate in some semblance unison. But if each of the once-independent component corporations used different standards – as they often did – coordination within the resulting vertically or horizontally integrated firm could prove immensely difficult, if not impossible.¹⁹

The individuals who secured the adoption of standards, both within firms and without, tended to be familiar with the literal nuts and bolts of the second industrial revolution. They were often engineers, scientists, entrepreneur or some combination of these. These individuals – astonishingly influential people like the machine-tool savant William Sellers, the engineer Robert Briggs, or the chemist Charles Benjamin Dudley – do not appear in Chandler’s account. And no wonder: these individuals occupied niches outside the big, leading industrial firms, or if they did, did not perform conventional managerial roles. Rather, they operated in the interstices of an economy increasingly defined by larger, hierarchical corporations, rather than within those institutions. But that did not mean they lacked power. Far from it.

Indeed, while the “managerial revolution” has much to recommend it as an explanatory device for a constellation of economic transformations in the Gilded Age and Progressive Era, it may be useful to consider whether there was an equally important and no less essential “engineering revolution” that took place alongside of it. This concept, which is borrowed from works by historians like Steve Usselman and the sociologist Yehouda Shenhav, offers a way to

¹⁹ White, *Railroaded*, 236. On corporate consolidation in the late nineteenth century, see Naomi R. Lamoreaux, *The Great Merger Movement in American Business, 1895-1904* (New York: Cambridge University Press, 1985).

broaden our understanding of the monumental transformations of business that took place in the late nineteenth and early twentieth centuries.²⁰ Standardization was one aspect of this technical revolution, and a particularly useful way to grasp its many layers, given the sheer number and diversity of firms, entrepreneurs, scientists, engineers, managers, and others who hammered out the first technical standards. But this will necessarily require that historians spend more time reading through the papers of individuals and institutions who operated outside the organizations that Chandler identified as central to the story.

This will also help rectify one of the most significant shortcomings of Chandler's work: his technological determinism. In almost all of his scholarship, Chandler referred to "technological imperatives" that mysteriously, if inexorably, gave rise to the managerial revolution. Chandler left himself open to this charge in no small part because he failed to actually see the transformation he was describing from the standpoint of the engineers and mechanics who built – and yes, standardized – the industrial infrastructure that made the managerial revolution possible in the first place.²¹ This was certainly true of the most visible technological icons of the era: the locomotive, telegraph, and steam engines. There is a history to the standardization of all of these technologies. But I want to focus on something far more banal, hidden, and unexceptional in order to highlight the centrality of standardization to the rise of the modern, corporate economy: screw threads.

Please understand that by "standard screw threads" I am referring to something different from ordinary screws. There is no overriding reason to standardize ordinary wood screws: slight

²⁰ Usselman, *Regulating Railroad Innovation*; Yehouda Shenhav, *Manufacturing Rationality: The Engineering Foundations of the Managerial Revolution* (New York: Oxford University Press, 1999). See also Noble, *America by Design*.

²¹ On Chandler's technological determinism, see Usselman, "Still Visible" and David A. Hounshell, "Hughesian History of Technology and Chandlerian Business History: Parallels, Departures, and Critics," *History and Technology* 12 (1995), 205-224; Thomas J. Misa, "Retrieving Sociotechnical Change from Technological Determinism," in Merritt Roe Smith and Leo Marx, eds., *Does Technology Drive History? The Dilemma of Technological Determinism* (Cambridge, Mass.: MIT Press, 1994), 115-142.

variations in the thread mean nothing when screws are used to connect two pieces of wood. Far different are screw threads that connect two pieces of metal together: a screw bolt and a nut, for example, or a screw that connects to a thread bored into a larger piece of metal. In order for these to fit together without stripping the metal, or without coming loose, the difference between them is extraordinarily small – sometimes as little as 1/5000th of an inch., as one technical report from the 1880s observed. This need for precision would only increase as screws and other comparable fastenings came to be used on machines such as cars and airplanes where vibrations could easily loosen poorly made fittings.²²

Though screw technologies date to ancient times, precision screw threads only became possible in the eighteenth century, when French screw lathes first came into use. But these remained primitive contraptions, and it fell to British mechanics such as Henry Maudslay and Americans such as David Wilkinson to turn these into machines into something capable of producing reliable, precise nuts and bolts. For the uninitiated, a lathe is basically a potter's wheel turned on its side, where you turn or spin a cylindrical object and cut into it using tools that are like teeth of hardened steel. The early screw lathes used what is known as a "master screw" to transmit a regular cut to an unfinished bolt. By fiddling with the gears that connected the master screw and the blank bolt, a mechanic could effectively cut the thread in a regular fashion, guaranteeing a certain pitch. These lathes, while originally used to cut screw threads alone, were

²² George M. Bond, *Standards of Length and Their Practical Application* (Hartford: Pratt and Whitney Corporation, 1887), 71. The best single work on screw threads remains Bruce Sinclair, "At the Turn of the Screw: William Sellers, the Franklin Institute, and a Standard American Thread," *Technology and Culture* 10 (1969), 20-34. Sinclair also discusses industrial standardization more generally in *A Centennial History of the American Society of Mechanical Engineers, 1880-1980* (Toronto: University of Toronto Press, 1980), 46-60. The only other studies of screw threads focus on European standards for scientific instruments. See Randall C. Brooks, "Standard Screw Threads for Scientific Instruments. Part 1. Production Techniques and the Filiere Suisse," *History and Technology* 6 (1988), 59-76 and "Standard Screw Threads for Scientific Instruments. Part 2. The British Association Screw Gauge," *History and Technology* 6 (1988), 45-59.

also used to cut pipe threads; indeed, the two branches of machine shop practice are closely related to one another.²³

In the nineteenth century, another method of cutting threads became commonplace using what are known as taps (which cut the threads inside nuts) and dies (which cut the threads on the bolts or actual screws). Both taps and dies could be used by hand as well as in machines that functioned like drills. This new approach was somewhat simpler, and more compatible with the needs of mass production. In the case of the lathe, the cutting tool remained stationary while the blank spun on its axis. By contrast, The difference between this approach and the screw lathe lay in was that here the blank bolt or nut would be held stationary while the tap or die cut away the metal. A lathe, by contrast, spun the blank while the cutting tool remained relative stationary.

Machine shops cut nuts and bolts according to their own idiosyncratic traditions or standards. This in theory enabled the various pieces to work together. They did, up to a point. But – and here’s the important part – the metal screw and bolts that one workshop produced were incompatible with those produced elsewhere. If you bought an instrument or machine held together by screw threads, you would need to go back to the original workshop for repairs. In all likelihood, a machinist would have to craft an entirely new thread from scratch, something that took hours to do under the best of circumstances.

What was true of screws, nuts, and bolts was true of all metal parts as the industrial revolution gathered steam. In the early to mid-nineteenth-century United States, manufacturers produced an ever-greater number of products, from reapers to sewing machines to clocks. For the most part, these were disconnected: it mattered little if one firm made goods to one set of internal standards, while other firms followed their peculiar standard. This babel of

²³ Robert Woodbury, *History of the Lathe to 1850* (Cambridge, Mass.: MIT Press, 1961); Edwin A. Battison, *Screw-Thread Cutting by the Master-Screw Method since 1840: Contributions from the Museum of History and Technology*, Bulletin No. 240, Paper 37 (Washington: Smithsonian Institution Press, 1964).

manufactured goods would remain common throughout the rest of the century, with small, specialized manufacturers churning out goods made of parts that, while often interchangeable with other parts produced by any given firm, did not resemble the corresponding parts produced by other firms.²⁴ A survey of standardization made by the engineer James See in 1888 thus detailed an astonishing degree of variation in, among many other things, shoes, wrench squares for water cocks, dental tools, braces and bits, roller skate wheels, sections of rolled iron, locks, chain pumps, printers' chases, fireplace mantels and grates, envelopes, bricks, and others.

Yet as See acknowledged, standardization had taken place in a number of key components, with screw threads the focus of the very first campaigns for technical standards. To understand why this happened, it is essential to understand that when we speak of "technology" during the second industrial revolution, we are increasingly talking about a system – elaborate concatenations of different technologies -- rather than a collection of discrete, disconnected machines. These systems could be modest, even banal: the networks of pipes that funneled natural gas, water, oil, and steam from one place to another. Far more elaborate, and visible, were the railroads, which assumed astonishing levels of complexity and geographical breadth in the nineteenth-century United States. The railroad contained systems within systems many times over; it was, as Chandler recognized, a technological network that demanded new ways of doing business.²⁵

Large, sprawling technological systems built on connections are peculiarly vulnerable to failure: a single loose bolt can halt a train, and by extension, an entire railroad. Likewise, the

²⁴ James W. See, "Standards," *Transactions of the American Society of Mechanical Engineers* 10 (1888-1889), 542-575. On the continuing importance of batch production and the barriers to standardization, see Philip Scranton, *Endless Novelty*.

²⁵ On this idea generally, see James R. Beniger, *The Control Revolution: Technological and Economic Origins of the Information Society* (Cambridge: Harvard University Press, 1986); Thomas P. Hughes, "The Evolution of Large Technological Systems," in Wiebe E. Bijker, Thomas P. Hughes, and Trevor Pinch, eds., *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology* (Cambridge, Mass.: MIT Press, 2012), 45-76.

safety of the entire system is only as good as the connections that keep the parts in play. Bad pipe threads could lead to natural gas explosions; steam boilers could detonate – and did. The lack of standardized parts amplified the risks of this happening because a lack of uniformity rendered it impossible to know, for example, if the strain that one bolt or thread could withstand might result in a catastrophic explosion elsewhere. And even if the breakdown was not dangerous, it was immensely inconvenient, with repairs requiring a bespoke approach to the problem. Factor in the fact that some of more complex machines in these systems – locomotives, for example – had thousands of bolts and couplings – and potential problems could multiply exponentially.²⁶

A lack of standards also frustrated the expansion of existing systems, or the absorption of competing systems. This became particularly imperative in the closing decades of the nineteenth century, when a burst of corporate mergers put many formerly independent firms under common management. Dozens of firms that had formerly operated independently now had to move in unison. Technical standards could, in theory, facilitate this kind of integration as well as foster the centralization desired by modern management. This was particularly the case with the railroads, where a lack of standardization frustrated efforts at system-building for much of the nineteenth century.

The first screw thread standards appeared in Great Britain in the city of Manchester, home to that nation's machine tool industry. Credit for the idea goes to a machinist and industrialist named Joseph Whitworth who had trained in Henry Maudslay's workshop. In an address to the Institution of Civil Engineers in 1841, he observed that the rail and steamship companies had to have as many different tools on hand as they had suppliers of screws.

²⁶ On standardization generally on the railroads, see Usselman, *Regulating Railroad Innovation*; Albert J. Churella, *The Pennsylvania Railroad, Volume 1: Building an Empire, 1846-1917* (Philadelphia: University of Pennsylvania Press, 2012), 578-581.

Whitworth attacked this “want of uniformity,” but recognized that there was no obvious candidate. In fact, surveying the screw threads in use, he found “instead of that uniformity which is so desirable, a diversity so great as almost to discourage any hope of its removal.”²⁷

Rather than propose an entirely arbitrary standard, Whitworth gathered sample screw bolts from around the nation and measured them. He then averaged his findings, arguing that this would constitute a kind of “compromise, all parties consenting got adopt a medium for the sake of common advantage.” In short, almost every one would need to alter their screw threads to make this system work, but most changes would be a matter of moving to the middle, rather than forcing a radical break with past practices. Whitworth’s system caught on in Britain, thanks in part to the fact that Whitworth became the exclusive supplier of most of the gauges, taps, and dies used to make Whitworth screws (and got very rich doing so). Whether this was Whitworth’s intent from the beginning is difficult to divine, though one prominent machinist in the United States believed that the 55 degree angle, which required complex machinery to cut, “was originated by Mr. Whitworth with...the view of keeping the business of supplying the world in his own hands...by giving an angle so difficult to be dealt with that people would prefer to come to him for their screw gear...”²⁸

Regardless of Whitworth’s motives, his standard never caught on in the United States, even if it has some adherents. Instead, machinists continued using a bewildering array of threads. These might vary by pitch (the number of threads per inch) in strange ways: a single 5/8th inch bolt might have 11 threads, or 11 ½ or 12 or even 11 ⅓ threads per inch. And that was

²⁷ Joseph Whitworth, “A Paper on an Uniform System of Screw Threads,” in *Miscellaneous Papers on Mechanical Subjects* (London: Longman, Brown, Green, Longmans, and Roberts, 1858), 30; A. E. Musson, “Joseph Whitworth and the Growth of Mass-Production Engineering,” *Business History* 17 (1975), 109-149; Norman Atkinson, *Sir Joseph Whitworth: ‘The World’s Best Mechanician* (Phoenix Mill, Gloucestershire: Sutton Publishing, 1996), 129-133.

²⁸ Whitworth, *Miscellaneous Papers*, 30; George R. Stetson, “Standard Sizes of Screw Threads,” *Transactions of the American Society of Mechanical Engineers* 1 (1880), 6.

just the pitch. The depth of the groove might vary, as would the angles of both the thread and the groove. The *American Railway Times*, writing in 1859, bemoaned that “instead of that uniformity which is so desirable, a diversity so great as almost to discourage any hope of its removal.” Likewise, in a number of editorials published in the early 1860s, *Scientific American* observed that “if there is any one thing in the transactions of the machine-shop more incomprehensible than another, it is the want of some settled size or number for screw threads.”²⁹

Yet the machine tool and metal-working industries resisted calls to standardize. This may have been a function of what one writer later described as the alleged “selfishness of manufacturers, who prefer their own fractional threads in order that repairs and reduplications must come from them.” There is likely some truth to this claim: in the closing decades of the nineteenth century, many manufacturing firms resisted calls of industry-wide standardization, believing that common standards would lead to ruinous cost-cutting. Differentiation, by contrast, permitted companies to flourish in their own niches, largely insulated from competitive pressures.³⁰

Absent some government edict, which would have been next to impossible to enforce, standardization would require a rather unusual mix of individuals and institutions to get it off the ground. The city of Philadelphia, arguably the center of the nation’s machine tool and metal-working trades at this time, came to play the most significant role. A number of key firms had their headquarters here, including the Baldwin Locomotive Works. The people behind these firms often belonged to the same families, making collaboration more possible. Many came from Quaker families, and they embodied that religion’s fetishization of consensus over conflict.

²⁹ “Proportions for Screw Threads,” *American Railway Times*, 21 May 1859, 11, 21; “The Pitch of Machine Screws,” *Scientific American*, 13 December 1862, 376; “The Size and Pitch of Machine Screws,” *Scientific American*, 3 January 1863, 6; “The Pitches of Screw Threads,” *Scientific American*, 10 October 1863, 233;

³⁰ “The Standard Screw Threads,” *Scientific American*, 9 February 1884. For an interesting theoretical take on these issues, see Stanley M. Besen and Joseph Farrell, “Choosing How to Compete: Strategies and Tactics in Standardization,” *Journal of Economic Perspectives* 8 (Spring 1994), 117-131

Moreover, almost all had some affiliation with the Franklin Institute, a private organization dedicated to disseminating technical knowledge that had far more influence than any other such organization, never mind the federal government itself.³¹

Philadelphia's industrial community, in other words, was well suited to craft a standard. In fact, two of its leading technical minds, Robert Briggs and William Sellers, promulgated some of the first technical standards in the nation. Briggs, who spent the 1840s and 1850s acquiring experience building iron pipes, came to Philadelphia in 1860 to become the Superintendent and Engineer of the Pascal Iron Works, makers of iron pipes and fittings. Briggs was the consummate modernizer, someone who, as a posthumous sketch of the man observed, brought "order out of chaos." His most lasting contribution was the adoption of a regular, standard system of pipe threads, couplings, and valves – the eponymous Briggs system that governs our pipes and tubes today. This standard originated in the early 1860s at the Pascal Iron Works, which under Briggs leadership soon became the nation's largest manufacturer of pipes, couplings, and fittings. It was in a position where it could easily set the standard, in that other firms had less to gain by going their own way. If they wished to connect to pipe manufactured by Briggs, they needed to adhere to his standard. And they did, though this took many years.³²

But I want to focus today another standard bearer of modernity named William Sellers. A mechanical prodigy, Sellers founded a machine tool firm that exercised a disproportionate

³¹ Bruce Sinclair, *Philadelphia's Philosopher Mechanics: A History of the Franklin Institute, 1824-1865* (Baltimore: Johns Hopkins University Press, 1974); A. Michael McMahon, "'Bright Science' and the Mechanic Arts: The Franklin Institute and Science in Industrial America, 1824-1976," *Pennsylvania History* 47 (October 1980), 351-368; Stephanie Morris, *The Franklin Institute and the Making of Industrial America* (Bethesda, Maryland: CIS Academic Editions, 1987). On the centrality of the machine-tool industry to solving technological problems, see Nathan Rosenberg, "Technological Change in the Machine Tool Industry, 1840-1910," *Journal of Economic History* 23 (December 1963), 414-443.

³² William J. Baldwin, "On Standard Cast-Iron Fittings," *Transactions of the American Society of Mechanical Engineers* 4 (1882), 274-287; George M. Bond, "Standard Pipe and Pipe Threads," *Transactions of the American Society of Mechanical Engineers* 7 (1885), 311-327. The Briggs standard likely began somewhat earlier in 1846, though it wasn't systematized until the 1860s. See the posthumous paper by Briggs, "American Practice in Warming Buildings by Steam," Paper No. 1842, *Minutes of the Proceedings of the Institution of Civil Engineers* 71 (1883), 95-123; "Robert Briggs," *Journal of the Franklin Institute* 115 (1883), 229-236.

influence relative to its size. One contemporary described him as the “greatest tool builder of his day and generation”; none other than Joseph Whitworth labeled him “the greatest mechanical engineer in the world.” Sellers had his own firm in Philadelphia. He also founded the Edge Moor Iron Company in 1868, which dominated the fabrication of the iron and steel components used in bridges and other large-scale projects; it was the largest such plant in the world at the time.³³

Sellers had a fetish for uniformity. In the mid-nineteenth century, most industrialists who built metal structures or machines tended to paint them different colors. Sellers, by contrast, adopted a “dull lead tint...known as ‘machine gray.’” Long before “form follows function” became the rallying cry of modern architecture, Sellers designed his machines with an eye to the precise role they would play. His “method of design,” one contemporary noted, was the “adaptation of the forms of his machine to the strains to be carried by them.” This preoccupation with efficiency went hand in hand with an obsessive drive to control those who carried out his wishes. The factory itself was a machine. “He knew how to give an order and exact obedience,” recalled one associate after his death, “and only to those who showed the capacity to obey did he extend the authority to direct the management of his affairs, while over all he never failed to exercise a masterly control.” Sellers went on to become president of the Midvale Steel Company, a corporation best known as the site of Frederick Winslow Taylor’s experiments in scientific management. Recent scholarship has suggested that many of Taylor’s ideas in fact originated with Sellers.³⁴

What does this have to do with screw threads? Understand that in a world where every nut and bolt – every screw thread coupling – was *sui generis*, skilled labor wielded astonishing

³³ “William Sellers,” *Journal of the Franklin Institute* 159 (May 1905), 365-381; Robert Kanigel, *The One Best Way: Frederick Winslow Taylor and the Enigma of Efficiency* (Cambridge, Mass.: MIT Press, 1960).

³⁴ “William Sellers,” *Journal of the Franklin Institute* 159 (1905), 365-381. On Sellers and Taylor, see Domenic Vitello, *Engineering Philadelphia: The Sellers Family and the Industrial Metropolis* (Ithaca: Cornell University Press, 2013), 146-147.

levels of control over the operation and maintenance of the nation's machines. By contrast, if a system of uniform screw threads could be established and mass-produced, building --- never mind fixing – those machines would require far less in the way of skilled labor. It would also move the locus of power away from the shop floor toward management. Indeed, from the perspective of an industrialist like William Sellers, a uniform system of simplified screw threads offered a means of “masterly control,” making his shop floor legible and transparent.

This helps explain the system of screw thread standards that Sellers presented in 1864 at the Franklin Institute. Rather conveniently, Sellers was also the president of the Franklin Institute, virtually guaranteeing that whatever he proposed would find a sympathetic audience. Sellers rejected the Whitworth standard, which he found wanting in several respects, particularly the amount of skill and special machinery that it entailed. The angle of 55 degrees, for example, “is a difficult one to verify,” argued Sellers. The Whitworth Standard required special tools, special gauges, and a great deal of expertise. By contrast, the committee appointed by Sellers to review his own proposal concluded that the Sellers thread “would enable any intelligent mechanic to construct it without any special tools...” This echoed Sellers's own position that “the problem of the day is not only how to secure more good workmen, but how to enable such workmen as are at our command to do good work...In other words, the attention of engineers is constantly directed to so perfect machine tools as to utilize unskilled labor.”³⁵

But there was more to this than control over the shop floor. The standard that Sellers proposed was already in use at his own machine tool factory. Whatever the many advantages of his standard – and there were many – other manufacturers would need to conform to his standard and assume the burden of retooling their establishments at their own expense. To some extent

³⁵ *Proceedings of the Franklin Institute* 77 (1864), 343-351. See also William Sellers & Co., *A Treatise on Machine-Tools, Etc. as Made by Wm. Sellers & Company*. Philadelphia: J. B. Lippincott and Company, 1877, 12-19, 113.

they were willing to do so, if even this meant sacrificing the advantages of their own peculiar systems of threads. Charles T. Parry, the Superintendent of the Baldwin Locomotive Works, observed that while “fine threads were best adapted for locomotive purposes, as they are more permanently secured when screwed up, than the coarse threads,” nonetheless conceded that “we would be glad to find a coarser thread acceptable, and would be willing to advocate it if by that means only, uniform standard threads could be adopted.” This pragmatism would become more common in succeeding years. As the engineer George See argued in the 1880s, “it is certainly better that these things should be uniform, than that a few should be better and many worse, and all different. Uniformity in such case is of itself a superior merit.”³⁶

But who, precisely, got to choose which standard should prevail? In the case of screw threads, not everyone was convinced that the Sellers plan was best. Critics included the formidable Robert Briggs, who advocated a modified version of the Whitworth system, and strenuously pressed his case within the halls of the Franklin Institute. But he was fighting an uphill battle against the president of the institution, and when the matter came to a vote, he lost.³⁷ From here the battle moved to other arenas, including the United States Navy, which created a board in 1868 to review the competing standards and deem one worthy of universal adoption. In the course of their investigations, they visited machine shops around the country, gathering information on the systems in use. Not surprisingly, the report found most of these to be “entirely without system.” Several establishments used variants of the Whitworth standard, but with the exception of a single firm, these strayed from the original prescription, intermingling with other local standards to create what the board disapprovingly classified as “mongrel”

³⁶ *Proceedings of the Franklin Institute* 79 (1865), 53-56; See, “Standards,” 546.

³⁷ Robert Briggs, “A Uniform System of Screw Threads,” *Journal of the Franklin Institute* 79 (1865), 111-125. Meeting Minutes, 15 November 1864, in Folder “Special Committee. Proper System of Screw Threads, Bolts, Nuts,” in Box “Special Committees,” Archives of the Franklin Institute, Philadelphia, Pennsylvania.

standards. The board likewise rejected the Briggs standard, largely because it could not be “scaled up” to encompass larger diameter bolts without sacrificing their ability to withstand strain. The Sellers system, by contrast, offered the appearance – some might say illusion – of a natural law, complete with universal constants. It was, the board concluded, a system “which, by the use of the formula, or equation of the curve representing its law, admits of indefinite extension.”³⁸

The Navy endorsed the Sellers system, ordering that work done on naval contracts conform to it, though the government had no further role in implementing the system. Not long afterward, important professional associations connected to the railroads – the Master Car-Builders Association and the Master Mechanics’ Association – urged its adoption on its members. This was imperative by the 1880s. As the *Journal of the Franklin Institute* noted in 1888, “since the exchanging of cars from one road to another has become so universal, the necessity for an interchangeable system of bolts and nuts has grown more apparent; and all the roads are falling into line in adopting the Sellers system.”³⁹ And this might well be the end of the story, if standardization depended only on the endorsement of a few key interest groups, corporations, and ostensibly neutral professional organizations like the Franklin Institute. But that is not what happened. Each turn of the screw, so to speak, led to consequences that neither Sellers nor other advocates of standardization could have foreseen.

To the extent that historians of technology contemplate standards, there is often a presumption that once a standard has been adopted, the rest is easy. Not true. In 1874, the New York, Lake Erie & Western Railroad adopted the Sellers system, proceeding to furnish a set of standard taps and dies to each of the machine shops on the line (a tap is a tool used to cut the

³⁸ United States Navy, *Report of the Board to Recommend a Standard Gauge for Bolts, Nuts, and Screw-Threads for the United States Navy*. May, 1868. Washington: Government Printing Office, 1880, 16.

³⁹ John. G. Gill, “Screw Threads,” *Journal of the Franklin Institute* 125 (1888), 187.

thread of a nut; a die is used to cut the actual screw thread on the bolt). In 1876, managers discovered that nuts fashioned in one shop failed to fit bolts cut at others. Nor would they fit with the nuts and bolts produced by other corporations' shops that had also adopted the Sellers standard.⁴⁰

What was going on here? Though some of the failures could be chalked up to sloppiness or failure to adhere to the standard, investigations turned up something more serious. At a meeting of the Master Car Builders' Association in 1879 to which William Sellers was invited, a committee appointed to look into the matter reported that the taps and dies manufactured and sold to machine shops as the Sellers standard differed in their dimensions. Why? The committee found that the manufacturers of these standard taps and dies relied on gauges to insure the accuracy of their wares. But the gauges, when examined, turned to be different as well, and "although the difference was not great, it was sufficient to prevent the bolts and nuts, made to conform to them, from interchanging with each other." As Sellers remarked at the meeting, "the difficult does not exist in the system of screw threads so much as it does in the matter of the original standard" – in other words, the definition of the inch.⁴¹

The establishment of such fundamental standards – so-called "metrological standards" -- has usually been viewed, on the rare occasions when it has attracted scholarly scrutiny, as a prerogative of the nation state.⁴² But in this instance, responsibility ultimately fell instead to a single private firm known as Pratt & Whitney. As the leading manufacturer of taps and dies, as well as gauges used to measure the accuracy of these templates, Pratt and Whitney set out to create a standard that could be reliably used in commercial work. The details of this are

⁴⁰ Bond, *Standards of Length*, 65.

⁴¹ Bond, *Standards of Length*, 66. See also George R. Stetson, "Standard Sizes of Screw Threads, *Transactions of the American Society of Mechanical Engineers* 1 (1880), 3-4.

⁴² See, e.g., James Scott, *Seeing Like a State: How Certain Schemes to Improve the Human Condition Have Failed* (New Haven: Yale University Press, 1998), 24-27.

technical, involving a remarkable partnership between the astronomer William A. Rogers at Harvard and machinists at Pratt and Whitney, the most notable of which was George M. Bond. In order to get to the “bottom” of the matter – to construct a system of screw threads on something genuinely concrete, a kind of ur-standard. Toward that end, Rogers obtained a transfer of a copy of the standard yard of the British Imperial Yard on deposit in the “Strong Room” of the Old Palace Yard in London. This was formerly known as “Bronze 19,” but after a fire destroyed the original standards, it became known as Imperial Yard No. 1.

In the end, Pratt and Whitney produced several yard measures that were as accurate – if not more accurate – than those on deposit at the Office of Weights and Measures. They built entirely new machines to do so, including a machine known as the “Universal Comparator.” After confirming that the standard on deposit at the Office of Weights and Measures matched its standards, the company began producing master screw thread gauges that could be sold to clients. In effect, the nation’s machine shops began coordinating their own production of screws with gauges guaranteed to match the master gauges – and by extension, the master units of measure – held in the vaults of Pratt and Whitney.⁴³ In the succeeding years, within certain industries – namely, the railroads – screw threads did move toward some semblance of standardization. But this process was gradual and halting. At the same time, the standardization of the very unit of measure made possible the distribution of accurate gauges in a range of metal-working industries, ushering in an age when it became possible to contemplate, if not actually institute, a more comprehensive set of product standards governing a range of components.

⁴³ Bond, *Standards of Length*, 1-49; George M. Bond, “Standard Measurements,” *Transactions of the American Society of Mechanical Engineers* 2 (1881), 80-90. On this episode, see also Richard Staley, *Einstein’s Generation: The Origins of the Relativity Revolution* (Chicago: University of Chicago Press, 2008), 65-132.

But as it did, it effectively closed the door to another project of standardization that had become one of the most visible emblems of metrological modernity: the metric system. By the late nineteenth century, the scientific community had endorsed its adoption, and it seemed as though Congress might well make it compulsory, having already legalized its use in 1866. But the machine tool industry – and in particular, the people involved in making nuts and bolts – frustrated these efforts. It would not be an exaggeration to say that the reason we do not use the metric system in the United States is due overwhelmingly to the path dependencies generated by the humble screw thread.

Coleman Sellers, a cousin and business associate of William Sellers, was one of the more vocal opponents of the metric system. In a series of broadsides intended for his fellow mechanical engineers and machinists – “The Metric System: Is it Wise to Introduce It into Our Machine Shops? – Sellers laid out the case against adoption. His brief against the metric system was not the backward, provincial mutterings of a xenophobe, but the arguments of a modernizer who had already chosen a path toward standardization that had, by the 1870s and 1880s, become irreversible.⁴⁴ As Sellers noted, “gradually, separate and distinct manufacturing establishments have come to use the same standards and to make their production interchange one part with another.” He cited the “screws and fittings for steam, gas and water pipes,” as well as the standards system of “screw threads for bolts and nuts” promulgated by his cousin. All of the nation’s machine shops contained tools for crafting these standardized items, all denominated in terms of the inch. These would need to be replaced, as would the dies, taps, gauges, and even the drawings that served as templates for the various parts.⁴⁵

⁴⁴ Coleman Sellers, “The Metric System: Is It Wise to Introduce It into Our Machine Shops?” *Transactions of the American Society of Mechanical Engineers* 1 (1880), 1-19.

⁴⁵ Coleman Sellers, “The Metric System in Our Workshops; Will Its Value in Practice Be an Equivalent for the Cost of Its Introduction?” *Journal of the Franklin Institute* 97 (1874), 381-391.

But it was the deeper, systemic changes that truly posed a problem for the metric system's adoption. As Sellers noted, "America has, for the last half century, been striving in its own way, towards equalization of its standard sizes. The immense railroad industries demand this. Standard wheels or standard axles – standard fit sizes for both – are all founded on an inch scale of sizes."⁴⁶ These components, from screw threads to railroad car couplings, constituted a vast, interconnected technical system founded on the inch. Adopting the metric system would therefore necessitate that every single piece of that system be changed. Change would not be discretionary. Nor, Sellers noted, would it be cheap. This argument carried the day from the 1870s onward. Throughout it all, the arguments of the mechanical engineers became the primary stumbling block toward adoption of the metric system. The humble nuts and bolts that knitted together the ever-growing technical infrastructure of the United States would not – could not – be readily replaced. And in the ensuing decades, repeated attempts at compulsory adoption of the metric system would founder on the people, practices, and things rooted in this system. Each technical standard adopted in the late nineteenth and early twentieth century further entangled the technological infrastructure of the United States in a deeper set of standards at odds with much of the rest of the world.

Here, then, was a paradox. As a coordinating mechanism, screw threads worked exceedingly well within national boundaries, and their very existence highlights an unappreciated dimension of the second industrial revolution that cannot be understood purely in terms of markets or hierarchies. At the same time, however, these mechanisms were increasingly out of step with the coordinating mechanisms devised by other players in an increasingly global economy. Like the large, vertically and horizontally integrated corporations that Chandler studied just as they began to disappear, the technical standards born in the second

⁴⁶ Ibid.

industrial revolution – as well as the fundamental units of measure that have served also served as coordinating mechanisms – increasingly look like things of the past.

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