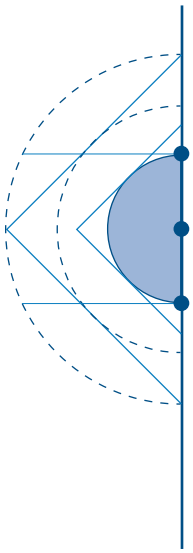

PART 1

The Measure of Progress: How Standards Have Shaped Order, Trust, and Innovation

Part 1 offers an overview of how standards have supported humanity's pursuit of order, trust, and innovation by mitigating risk, establishing consistent practices, and upholding quality and safety.

Chapter 1 examines the history of standards, from ancient systems of measurement to modern digital protocols, demonstrating how standards have served not only as technical tools, but also as means of coordination, authority, and exchange, supporting the governance of empires, the expansion of trade networks, and the advancement of science and industry. Developments in these areas have significantly contributed to nation building, market integration, and international cooperation, acting as catalysts for economic transformation.

Spotlight 1 illustrates how standards drove the East Asian development miracle in the second half of the twentieth century. The region's impressive success relied on three connected factors: strong state capacity to orchestrate systems of standards; export-driven strategies for growth to encourage upgrading of standards of quality; and the alignment of standards in smaller companies with those of leading firms, both international and domestic, for knowledge transfer.

Overall, part 1 examines both the pragmatic and the political factors underlying the expanding universe of standards. These include multiple trade-offs in the

development, adoption, and adaptation of standards to local contexts, the political forces that shape standards in situations in which large commercial and national interests are at stake, and the gaps, in the case of mandatory standards, between adoption and compliance. Part 1 sets the scene for the discussion in part 2 of the various types, forms, and functions of standards—and the crucial role of compliance.

1 A History of Standards

Main messages

- The evolution of standards reflects humanity's pursuit of order, trust, and innovation through harmonization of practices and mitigation of risks.
- *Measurement standards*, embedded in common understanding of units—as backed by metrology, the scientific study of measurement—have played a key role in projecting authority, building states, and strengthening markets.
- *Quality standards* have been essential in managing the risks that often come with new technologies and providing the assurance that ensures widespread adoption. Yet these types of standards have often been initially resisted until costs to public welfare become politically expensive.
- *Compatibility standards* have underpinned the diffusion and adoption of technologies, including those ushered in by each successive Industrial Revolution.
- Standards play an important role in managing risks arising from new technologies as well as in a wider understanding of negative externalities resulting from the expanding ecological footprint of industrialization and growing levels of consumption. Such standards matter for the quality of life: the deeper fundamental goal of development.
- Variations in social values, risk tolerance, market forces, and regulatory capacity affect the type and scope of standards.
- Standards often entail trade-offs. In the area of developing standards, these include inclusion of stakeholders versus speed and expertise versus capture. During the process of adopting standards, trade-offs exist between cost and quality, scale and diversity, and innovation and technology lock-in.

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Introduction

Nearly 4,000 years ago, a dissatisfied customer in the Mesopotamian city-state of Ur penned the first recorded complaint in human history.[1] The complaint, written on a clay tablet with cuneiform script—a flourishing example of a standardized medium used for formal communication across parts of the region—charges a copper trader, Ea-nāṣir, with several breaches of commercial expectations: the delivery of substandard copper, significant delays in transportation, and the mistreatment of his servant.[2] The dispute arose from a difference in measurement systems used to weigh copper at source and destination;[3] the allegation of the servant's mistreatment further suggests expectations of basic normative labor standards.[4] The complaint—and the copper consignment it describes—traveled through a network of messengers and caravans, illustrating the standardized infrastructure that supported communication and long-distance trade. Transactions relied on a standard silver-based monetary system for payments, supported by standardized administrative procedures: Scribes recorded accounts on clay tablets, sealed them in protective envelopes with cylinder seals, and archived them systematically.[5]

This story captures just how intertwined standards have been in human history, forming a codified ecosystem in terms of linguistics, commerce, measurement (metrology),[6] money, and labor, that has mediated trust, coordination, and value since ancient times.

This chapter paints a broad historical canvas highlighting the three typologies of standards that are the focus of this Report: measurement standards, quality standards, and compatibility standards. Although measurement standards emerged in the premodern era, each of these types of standards grew over the course of the Industrial Revolutions that have marked the modern era, beginning with the First Industrial Revolution—the "age of steam"—beginning in the mid-eighteenth century. Demand for standards skyrocketed during the late nineteenth century with the Second Industrial Revolution. The new "machine age," defined by mass production, complex technologies with network externalities in transport and telecommunications, urbanization, and global integration, spurred needs for compatibility and quality standards underpinning safety. The dawn of the Third Industrial Revolution in the second half of the twentieth century—the "information age"—turbocharged the need for compatibility standards, which were vital for the internet revolution. It also marked a structural shift in economies from manufacturing to services, the many components of which would again need their own standards. At the same time, the environmental fallout from two centuries of technological changes and economic growth made the need for environmental standards clear.

Measurement standards

Early standards focused on basic measurement and aimed at establishing political control and facilitating commerce. "Man learned how to measure centuries before he learned to write, and it was through measuring that he learned to count. In the list of talents which sets man apart from other animals, his ability to measure ranks among the highest," John Perry noted in *The Story of Standards*.[7] Measurement was thus not only a practical skill, but a significant cognitive advancement that enabled humans to conceptualize. Initially, "man was his own measure": Distances were gauged using the breadth of a finger, the span of a palm, or the length of an arm. These measurements, though imprecise and variable across individuals, sufficed when tasks were solitary and needs immediate.[8]

However, cooperative labor exposed the limits of measures based on the human body. When two workers used their own feet or arms to measure, their outputs would often be inconsistent.

To resolve this, measurements were often based on the dimensions of a leader, then encoded into physical proxies—such as measuring rods—for wider replication. In monumental constructions such as the pyramids, this logic was institutionalized with a single master standard embodied in a permanent object to ensure uniformity across dispersed labor groups.

In ancient Egypt (c. 2700 BCE), the royal cubit (*mahe*), a rod of 523 to 525 millimeters subdivided into seven palms and 28 digits, emerged as the primary standard. Precision was achieved through cubit rods made of wood or stone, used in constructing the Great Pyramid of Giza.[9] The *khet* (a 100-cubit rope) standardized land surveys and tax assessments. The Roda nilometer, calibrated to the cubit, transformed Nile flood levels into measurable data, supporting agricultural planning and famine prevention.[10] Standards developed in parallel in the Indus Valley, where the standardized "Indus foot" supported a modular regime for construction that centered on bricks with consistent proportions of 1:2:4.[11] Mesoamerican civilizations similarly relied on calibrated measures,[12] and in the Roman system of engineering, measurement underpinned large-scale water management.[13]

Beyond linear measures, standards measuring weight and volume formed the basis for trade, taxation, resource management, and administration. As seen in the Ea-nāṣir complaint (c. 1750 BCE), disputes over weights could undermine trust in decentralized trade systems. In Sumer, where barley grains initially served as units of weight, merchants exploited natural variation by selecting larger grains to skew measurements.[14] To counter this, durable stone weights and balance scales appeared independently in Egypt, the Indus Valley, and Mesopotamia about 3000 BCE.[15] By the second millennium BCE, long-distance merchants had established weight standards that had diffused across Europe, creating what may be considered the first common Eurasian market more than 3,000 years ago.[16] More than 2,000 weights, the use of which spanned 5,000 kilometers and 2,000 years, consistently fell within a narrow range of 8 to 10.5 grams, from Britain to Mesopotamia. Merchant interaction and self-regulation, rather than political decree, best explain the diffusion.[17]

Conversely, some ancient states institutionalized measurement through codified governance, deploying administrative oversight to ensure reliability and maintenance. In India, the *Arthashastra* (thought to have been written sometime between 321 and 296 BCE) mandated a Superintendent of Weights and Measures to oversee standard tools, penalizing traders with a 25 percent tax on the value of any goods they sold that failed to comply with the standards.[18] The legal regime established during China's Qin dynasty (fourth century BCE) enforced uniformity via state-cast bronze *sheng* (pints) and *jin* (weights), inscribed with edicts, a policy expanded to assert central authority following unification of the empire (221 BCE).[19]

By the medieval period, basic measurement standards had emerged as an important tool of governance: Monarchs recognized that a stable and thriving economy could enhance royal revenues while extending rulers' jurisdictional control.[20] Enforcement, however, proved difficult, hindered by limited administrative reach and resistance from local authorities and populations. Private franchises controlled markets, and violations of royal standards carried little stigma, undermining enforcement.[21]

Nonetheless, these standards served a vital symbolic function. The measurement tools they employed served as a legitimating mechanism for authority, linking the material and the metaphysical through the codification of standards. Although metrology reduced transaction costs, it was also rooted in promoting political goals—projecting state power and enabling state building—a role it maintained in later eras.

Two additional measurement standards discussed later in the Report also have antecedents in the

premodern period. Early standards for human capital, in the form of building skills, emerged in Europe in the second millennium, with the measurement of skills and products internalized within guilds. These bodies enforced the duration of apprenticeships and production quality, building competencies that ensured the compatibility of crafts across many parts of Europe for nearly eight centuries until guilds were abolished in the nineteenth century.[22] Guilds were "private order" institutions that generalized trust and built social capital, allowing them to address various forms of market failure. The apprenticeship model coped with imperfections in markets for skilled training, and quality certification by guilds addressed information asymmetries between producers and consumers of goods. But guilds also regulated entry into their occupations and strove to keep prices high by limiting output, suppressing competition, and blocking innovation, serving as an early cautionary tale regarding the need for open standards in some instances.[23] Eventually, the artisanal skills they represented succumbed to the power of the First Industrial Revolution.

Another contemporary challenge for development, building stronger governance through better standards for recruitment, also has long historical antecedents. China's examination system for civil service, operating over a millennium, pioneered how to measure competence for a "meritocratic" bureaucracy.[24] Yet family background significantly influenced success on the arduous examinations because of superior access among certain classes to social and cultural capital,[25] a pattern also observed in other contexts like France.[26]

The First Industrial Revolution and the beginning of modern metrology

The First Industrial Revolution—what some have termed the steam age—began in Great Britain in the second half of the eighteenth century, driven by coal, iron, and textiles. Standards began to have greater importance during this revolution in three distinct ways: in the development of new technologies, the diffusion of those technologies, and the management of risk from those technologies. Metrology (embodied in the metric system) and safety standards (through regulation of steam boilers) illustrate how standards began to seep into the modern era.

Metrology had barely advanced over the prior millennium. A sixteenth-century European treatise advised deriving a measuring rod from the footsteps of 16 men "as they leave church."[27] The feudal system fragmented political authority and, with it, metrology, which had become an embodiment of power. Each authority (king, lord, town, monastery) defined units under the principle "a king, a law, a weight, a measure." All this changed with the advent of the metric system.

The metric system: The confluence of political and measurement revolutions

The birthplace of the metric system was revolutionary France. Metrological chaos reigned in France through the 1700s, with about 250,000 localized weights and measures. Even a single measure, a pound of weight, was different for different commodities such as wheat, barley, and flour. With feudal lords controlling standards to extract fees, this huge variety in measures impeded trade and taxation among regions, undermining the monarchy's political authority, and likely impeded technological development as well.[28]

Demands for uniform weights and measures ranked among the top grievances of the bourgeois and working class, reflecting frustration with feudal arbitrariness and administrative inefficiency.[29] The revolutionary government of the 1790s framed metrological reform as both a scientific and an ideological project and tasked the

French Academy of Sciences with devising a system rooted in nature and reason, rejecting anthropocentric units like the *pied du Roi* (King's foot) in favor of universal, immutable standards.[30] Political and metrological revolutions were intertwined: The drive for standardization reflected broader ideals of rationality and equality. Universality became the core promise of the metric system: "for all people, for all time."

The metric system's certification process mirrored revolutionary state building. The Academy of Sciences, now an arm of the state, deployed expeditionary teams to measure the Earth's meridian and produce platinum prototypes for the meter and kilogram, embedding scientific authority into governance.[31] By 1795, the system was codified into law, with a decimal structure that symbolized a clear departure from the past. Conversion tables, pamphlets, and physical standards were distributed to municipalities; education in the metric system was made compulsory; and the state issued standards, hired inspectors, and imposed penalties for failure to conform with the standards.[32] The fact that uniformity in weights and measures would reduce diversity and weaken regional identities was seen as essential to forging a unified nation.[33]

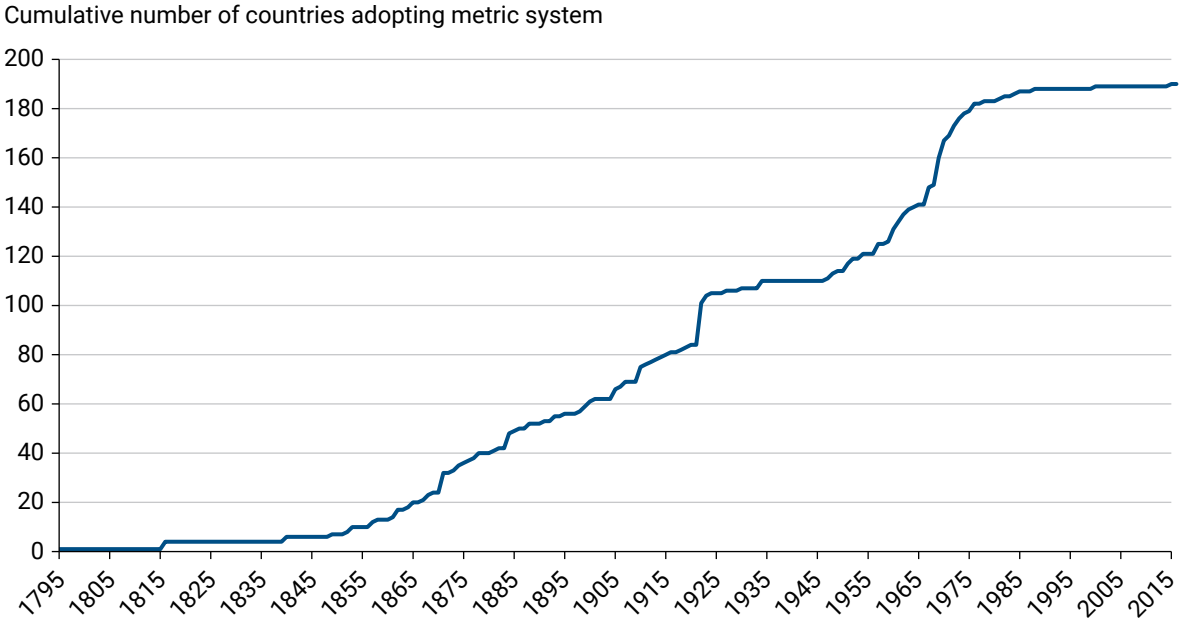
Despite the promise of metrification, its implementation was a fraught process. The revolutionary government framed it as a tool for dismantling feudal hierarchies and creating legally equal citizens, but the populace often saw its implementation as coercive. Artisans and peasants, reliant on familiar local units, maintained dual systems, sometimes marking old measures on new tools.[34] Shopkeepers exploited the transition by rounding up prices during conversions, and bureaucrats and surveyors quietly persisted with traditional units, undermining the system's credibility.

Napoleon's 1812 compromise, allowing traditional measures alongside metric ones, underscored the limits of top-down standardization and the essential role of trade-offs in the development and implementation of standards. Though the metric system became legally required in contracts, taxation, and education, everyday commerce remained in a hybrid space.[35] This duality underscored a central paradox: The metric system, conceived as a tool of emancipation, relied on authoritarian enforcement that alienated the very citizens it purported to empower. Only through decades of state pressure, generational change, and the 1840 reinstatement of mandatory use of the metric system did it gain full traction in France.

Initially, the metric system spread across Europe largely as a result of Napoleonic conquest. Although universality was its stated aim, it advanced "in the wake of French bayonets,"[36] just as British standards spread with its empire. The metric system's adoption was as much about symbolism and nation building as utility: from Italy's Risorgimento, to Germany's unification, to nineteenth-century Latin America (Argentina, Chile, Mexico) and postcolonial states in the twentieth century.[37]

Two new drivers for the metric system emerged in the later part of the nineteenth century: the expansion of science and technology and a spurt in cross-border movements of goods and information, marking the advent of the first age of globalization. The 1863 Paris Postal Conference led 15 nations to adopt metric weights for postal services, affecting 95 percent of global correspondence.[38] The dual purposes of national cohesion and international interoperability culminated in the 1875 Treaty of the Metre. Signed by 17 nations (including the United States but not Great Britain), it created the International Bureau of Weights and Measures (BIPM), which distributed certified prototypes of the meter and kilogram to member states.[39] As in France, global adoption of the metric system was slow, spanning more than a century (refer to figure 1.1). There were some

Figure 1.1 It took more than a century for the metric system to spread around the world



Source: Vera 2011, 494–97.

Note: The most recent adopter of the metric system, Samoa, joined in 2015.

notable exceptions, however. Despite early support from Thomas Jefferson and Great Britain's 1864 permissive law, neither Great Britain nor the United States fully adopted the system.

The introduction of the Système International d'Unités in 1960, which incorporated new measurements encompassing electrical, thermal, and luminous units, codified the metric system as the cornerstone of the world's metrological standards. But these standards were not static and have evolved with scientific advances.

India provides an example from a developing country of how common metrological standards provided a path toward national economic integration in a highly diverse society (refer to box 1.1).

Increasing precision in measurement has characterized each Industrial Revolution. Cumulative leaps in measurement precision have opened the door to new industries, from mechanical tolerances of one millimeter in the eighteenth century (enabling production of steam engines and screws) to industrial tolerances of thousandths of an inch in the nineteenth (mass production) to micron tolerances in the twentieth (electronics) to atomic-scale tolerances today (quantum technologies). Indeed, it has been argued that civilization's technological advances are directly tied to escalating achievements in precision.[40]

Box 1.1 How India used standards for state and nation building

Whereas nation building traditionally has been built around a common language, India's constitution, adopted in 1950, accorded official recognition to 14 languages (which later increased to 22). In this context, building a common set of metrological standards provided an alternative instrument for fostering national integration.

Despite colonial efforts toward standardization starting in 1833, including the 1870 Indian Weights and Measures Act, weights and measures in India remained fragmented, and a hybrid system of imperial and local units persisted. In 1934 the Indian Science Congress Association urged the colonial government to standardize weights and measures and adopt the metric system. Indian industry and scientific associations began putting pressure on the government for metrological reform. One of the first acts of the new government after India achieved independence from Great Britain in 1947 was to set up the Indian Standards Institution (ISI) to operate the country's certification marks scheme and facilitate consumer protection. Concurrently, the government set up the National Physical Laboratory of India to become the country's laboratory for calibrating measurement standards.

When India's first National Sample Survey went into the field in 1950, its results revealed a striking lack of standardization of weights and measures in rural areas: 143 different systems for measuring weight, 150 different systems for measuring volume, and 180 systems for measuring land area. These findings renewed support for switching to the metric system, with a new framing stressing that "Indianizing" the metric system was culturally more appropriate than unifying metrology on the basis of British imperial units, with their colonial baggage. India formally adopted metric units in 1956, implemented them legally in 1958, and made them mandatory by 1962.

The transition to the metric system demanded immense amounts of planning: new technical standards, public education campaigns, multilingual materials, and revisions to school curriculums. Indian Railways, the country's largest industrial employer, had to revise more than 35,000 standard drawings, but a shortage of draftsmen slowed the process. The limited capacity for manufacturing metric instruments stretched the transition across a decade.

Although metrology was one instrument, nation building also required a common set of standards for physical connectivity across a vast country, a role for which Indian Railways was ideally suited. But although railways connected the country physically, they employed three incompatible gauges (the width between rails): broad, meter, and narrow. This fragmentation led to inefficiencies, from maintaining different sets of rolling stocks to rerouting people and goods to ensure continuous journeys. Integration of railway gauges began in the early 1950s, with broad gauge selected as the standard, but advanced slowly. By the early 1990s, half the country's railway network still did not use broad gauge. In 1992, Project Unigauge was launched to convert all tracks to broad gauge. The process required new infrastructure and took another three decades. By 2022, a unified broad-gauge system of railways connected nearly the entire country. This single gauge made connectivity seamless and eliminated the need to have duplicate rolling stock to accommodate the different gauges.

(Box continues next page)

Box 1.1 How India used standards for state and nation building *(continued)*

India became the first Commonwealth country to switch to the metric system in 1956. However, despite this early start, the focus on standards declined during India's protectionist decades. Without market competition or export pressures, manufacturers had little incentive to meet higher standards. Moreover, the dominance of the public sector further reduced pressures to improve quality, which was not a priority in India's Five-Year Plans. Only after the country's 1991 liberalization, which ushered in a more open trade regime and increasing foreign direct investment, did standards slowly regain prominence in India's development strategy. Periodic conclaves on national standards began to be organized in 2014, leading to the formulation of the Indian National Strategy for Standardization in 2018.[a]

Source: Kapur and Subramanian 2025.

a. Kaul (2025).

Quality standards

Like those for measurement standards, the antecedents of quality standards date back millennia. The Code of Hammurabi (c. 1750 BCE) in ancient Mesopotamia included concerns about building standards, along with 282 laws that specified punishments for a wide variety of infractions, including harm caused by a poorly constructed home or building. It covered prices of construction and contractor liability and established the concept of civil damages, whereby defective work requires compensation, a concept that persists to this day.

The advent of the First Industrial Revolution made the importance of quality standards more evident. Initially rooted in standards for industrial safety, quality standards spread to other domains. Unsafe practices in increasingly concentrated urban areas, mounting pollution hazards from industrialization, and hazardous practices in lengthening food supply chains all brought safety—and the quality standards underpinning safety—to the fore. Before the First Industrial Revolution, safety requirements were determined locally and, in the case of Western Europe, by professional guilds. But the novel and widespread technologies unleashed by the Industrial Revolution posed new hazards. The sources, degree, and manifestations of the risks would change as new technologies emerged, but the basic questions around how to manage these risks and provide quality assurance would be perennial, from boilers in the nineteenth century to artificial intelligence in the twenty-first. The cases that follow hold a number of lessons that later chapters discuss further.

Regulating exploding boilers

Driving the First Industrial Revolution was a new source of harnessed energy: steam, generated (largely) by coal-powered boilers. However, these boilers posed significant risks to safety. The major industrial powers—France, Germany, Great Britain, and the United States—chose different ways to put safety standards in place to limit the risk that steam boilers would explode.[41] The variation in the methods they selected illustrates that compared with other types of standards, safety standards, with respect both to the levels and to the manner of regulation, are more specific to context, reflecting variations in social values, risk tolerance, and regulatory capacity.

As the pioneering nation of the First Industrial Revolution, Great Britain had thousands of boilers in use by the early nineteenth century. However, despite numerous accidents involving boilers, it repeatedly rejected legislation that would have mandated safety standards. Imposing such standards retroactively would have been costly, since a large number of boilers were already operating, and enacting standards for new boilers while grandfathering older equipment would have created unfair competition. British industrialists opposed government interference, citing property rights and favoring self-regulation, arguing that safety and profit were aligned: Avoiding explosions was in entrepreneurs' best interest. Moreover, they distrusted scientists, believing engineers and capitalists had greater practical knowledge. Despite a string of accidents and parliamentary inquiries, steamboat boilers were not regulated until 1852, and industrial boilers remained unregulated until 1902.

France imported high-pressure steam engines from Great Britain after the Napoleonic Wars. But the French government imposed safety standards on boilers early, even though there were only about 200 steam engines in use in the country and there had been few accidents. The relative underdevelopment of steam technology meant that the French state faced fewer entrenched interests from both capital and labor than did Great Britain. The French Revolution had already disrupted older guild structures, and the new technology lay outside existing trades. The government, confident in science, believed it could impose a nationwide standard grounded in mathematical principles formulated by the Academy of Sciences. A central commission oversaw regulation, inspecting boilers annually and certifying them with official stamps.

Comparing the British and French approaches to regulating risk

The differing British and French approaches highlight fundamental questions about ensuring safety and the role of governance in ensuring compliance with safety measures. France pursued safety through standards for product design brought to bear before manufacture, whereas Great Britain leaned on mechanisms put into play after equipment entered into service, namely, insurance and maintenance. In response to several dozen explosions of steam boilers occurring each year and mounting public pressure, Great Britain passed the Factory Act of 1844 (which imposed safeguards on the moving parts of machinery) and the Ordinance on Marine Steam Boilers in 1852. Entrepreneurs realized that they either had to solve the problem of the explosions themselves or risk having the government intervene. French-style standardization was ruled out on the grounds that it would increase the cost of boilers and subject industrialists to further government intrusion into their factories. Initially, the idea of insurance was resisted on the grounds that with the backup of insurance, boiler owners would become complacent about safety (moral hazard). But over time, the insurance model prevailed. The technical emphasis also diverged between the two countries: French engineers concentrated on structural specifications such as boiler thickness and valve diameter. British insurers, in contrast, made maintenance practices and boiler age the priorities, using these as the bases for setting insurance premiums.

By 1865, approximately 10,000 boilers in Great Britain were insured. Two decades later, that figure had grown to about 50,000, half of the national total. Insurance had as its purpose prevention of explosions, not compensation. British insurers focused on assigning liability to entrepreneurs to give them incentives to behave responsibly. French mining engineers, by contrast, often assigned blame to workers, sidestepping their own failures in design or oversight.

The contrast highlighted fundamental questions about who sets standards and how they are enforced. In France, annual government inspections were the norm; in Great Britain, insurance

companies conducted up to five inspections per year. This made the British system more effective in principle. Yet as noted earlier, as of the 1880s, half of all boilers in Great Britain remained uninsured and thus uninspected. In the 1860s, the explosion rate in both countries hovered around 6 per 10,000 boilers annually. However, for insured British boilers, the rate dropped to 2 per 10,000, meaning the insured boilers were safer than their French counterparts, but the uninsured ones were more hazardous.

The rigidity of French standards of safety may have constrained technological diffusion. Steam engines proliferated more rapidly in Great Britain. By the 1860s, France had about 25,000 boilers compared with 80,000 in Great Britain. By the 1880s, the figures were 60,000 and 120,000, respectively. However, it is hard to separate the role of standards from other economic factors, given the advantages British firms had as a result of cheaper raw materials and wider use of machine tools.

Eventually, the French safety regime also shifted from government toward industry associations and insurers. Political activism, particularly in the form of labor movements, played a key role in advancing workplace safety. By the mid-nineteenth century, workers began to demand better working conditions, including workplace safety. Ultimately, safety was not just a technical matter but a political one as well, shaped by the balance of power among entrepreneurs, labor, and regulators.

The story differs in other emerging industrial powers of the time. Germany adopted a more centralized approach, and earlier than either France or Great Britain. Prussia enacted legislation on boiler safety in 1831 and detailed general requirements in its 1845 Industrial Code. As a result, it had the lowest explosion rates for boilers in Europe. In contrast, the United States had the highest rate among industrial countries, followed by France and Great Britain. In fact, as many boilers exploded in a single month in the United States as did in a year in Germany, despite similar numbers of steam engines (refer to table 1.1).

Table 1.1 Risks from steam boilers varied widely across countries in the late 1800s because of very different approaches to safety

Per 10,000 steam boilers, 1882–92

COUNTRY	NUMBER OF EXPLOSIONS	NUMBER OF PEOPLE KILLED
United States[a]	20	29
United Kingdom	4.9	2.4
France	4.8	4.7
Germany	2.2	1.4

Sources: Crum 1910, 17–18; Hunter 1985; MTPTC 1988; Thurston 1907, 717.

a. The widespread use of steam boilers in remote sawmills, employing low-quality machinery with minimal oversight regarding safety, contributed to the greater frequency of explosions of steam boilers in the United States.

Most early American explosions of steam boilers occurred on steamships. As in the United Kingdom, steamboat owners and boiler manufacturers had the attitude that no respectable manufacturer would risk its reputation in constructing a defective boiler; constant examination of boilers would cause serious inconvenience without any guarantee that such examination would ensure public safety; and the sheer range of different boiler and engine designs made it next to impossible to agree on methods of examination. Enlightened self-interest of an entrepreneur would suffice to guarantee the public's safety. These arguments weakened legislative efforts, but as fatalities mounted, stronger federal legislation passed in 1852. However, the law covered only marine boilers, leaving out factory and locomotive boilers. It took two serious explosions in shoe factories in Massachusetts in 1905–06 that killed dozens for the state to enact

the first code for stationary boilers in 1907. Other states followed suit until there were so many different codes that manufacturers requested a body of professional engineers, the American Society of Mechanical Engineers (ASME), to address the issue. The result was the first Boiler and Pressure Vessel Code, published in 1915, a single volume encompassing 114 pages. By 2001, the code had grown to 28 volumes with more than 16,000 pages, and it grew further, to 33 volumes and more than 19,000 pages, between then and 2025.

This short history of safety standards for boilers offers several lessons that later chapters explore further. First, the achievement of safety depends as much on regulations and institutions as on social demand, whether from workers for a safer industrial environment, or from consumers for a safer product.

Second, the method of regulating safety standards depends on context. Even as Great Britain chose the private insurance route and blocked all attempts to introduce legislation requiring inspection of steam boilers on land by an official agency, it introduced such legislation in its largest colony, India, finding the British model "impractical" for India based on evidence showing "unanimously the popularity of official inspection and the confidence resulting from the fact that it is done by a Government agency."[42] That confidence would lead to boiler inspections' becoming the epitome of the "inspector raj" in independent India.

Third, there is a tendency to underinsure (limiting an insurance company's liability), because firms find more value in obtaining insurers' inspection service than they do in holding the insurance. According to one estimate, for every dollar they collect in premiums, insurance companies spend more than 22 cents on inspection services, whereas they pay 50 cents to policyholders for losses.[43]

Fourth, performance standards can induce innovation, as safety norms for boilers resulted in greater efforts to study ways of improving boiler efficiency and design. But standards need to evolve with new technologies, or they can hinder innovation.

Finally, the tendency for standards to proliferate appears inexorable. But whereas the need for planting new trees of standards for each new need seems obvious, the cumulative implications for the larger forest of standards are less clear.

The growing importance of safety standards: Fires, foulness, and food

Fires

The Second Industrial Revolution also drove a broader structural transformation marked by rapid, unregulated urbanization. A predominantly rural society had become overwhelmingly urban. Overcrowding, wretched housing for the working class, and substandard infrastructure (especially water and sewage systems) left cities highly vulnerable to catastrophic fires, prompting demand for standards of fire safety.

The groundwork for regulation in the area of fire safety was laid in the Middle Ages in Great Britain. The Great Fire of London in 1666 marked a turning point. The destruction it wrought, exacerbated by timber construction, narrow streets, and rudimentary methods for fighting fires, led to the Rebuilding of London Act the next year. The act mandated brick or stone construction, party walls, wider streets, height restrictions, and—critically—the appointment of building inspectors, or "surveyors," with enforcement authority.[44] The regulatory framework the act provided became the prototype for building codes worldwide and established the fundamental principle that public safety could justifiably limit private building practices.

Two centuries later in the United States, the Great Chicago Fire of 1871—and subsequent catastrophic fires—killed thousands of people, rendered many more homeless, and destroyed countless buildings and neighborhoods. The human, physical, and

financial costs of these deadly fires drove demand for standards in urban planning, building standards, codes governing fire safety, and standards for firefighting equipment. These included new standards mandating tile roofs and the use of internal steel structures; requirements for outward-opening fire exits, unlocked doors, fireproof stairwells, and clear signage; and occupancy limits. Experts—often working between government, insurance, and industry—began codifying fire safety. The Great Baltimore Fire of 1904 needlessly spread because the numerous fire companies that had traveled to help fight the fire had equipment that was incompatible with the local fire hydrants and could not hook up to them. The disaster prompted the National Fire Protection Association (NFPA) to publish standardized codes for equipment in 1905. Adoption, however, was slow. A decade later, only 287 of 8,000 US cities had adopted the code's standards, highlighting the challenges of voluntary compliance, even after catastrophes.[45]

Sprinkler systems were an early innovation in fire safety but lacked consistency. In the Boston area alone, nine different standards existed for sizes and spacing of sprinkler pipes. Insurance companies, bearing much of the losses related to fires, helped form the NFPA and promoted the first standards for sprinkler installation. The electrification of homes and factories added new fire hazards. Multiple overlapping standards for electrical construction created confusion and risk, prompting the creation of the National Electrical Code in 1897. Around the same time, Underwriters Laboratories (UL), a private initiative, was founded in Chicago to test and certify product safety. A century later, UL certification would appear on billions of consumer products worldwide.[46]

Two workplace disasters a century apart, New York's Triangle Shirtwaist Factory fire (1911) and the Tazreen Fashions factory fire in Bangladesh (2012), exposed similar failures in protocols for exit access and safety. In both cases managers had locked most exits to prevent theft and unauthorized breaks, trapping workers, mostly young women, inside the burning buildings. At the time of the Triangle Shirtwaist Factory fire, annual per capita income in the United States was US$333 (about US$10,000 in 2012), whereas in Bangladesh at the time of the Tazreen Fashions fire, it was less than US$1,000. Whereas the former was a turning point in the histories of both labor and building safety as a result of domestic pressure, in the case of the latter, the shift came as a result of pressure from foreign firms importing the country's products. These tragedies created an awareness that workers deserved protection regardless of economic status.

Standards that affect public safety require building public trust, a process that requires patience and incorporating lessons of tragic failures. Yet the push for safety to reduce fire risks has always run up against risky behavior driven by financial motives, especially reducing costs by scrimping on safety codes for buildings and on firefighting equipment, overcrowding, and so on, on the one hand, and weak mechanisms for ensuring compliance with requirements, on the other. As the built environment expanded, so did building codes to strengthen public health and improve safety. That would invariably add to costs, highlighting the perennial tension between reducing risks and escalating costs.

Foulness

Although the Second Industrial Revolution is often associated with railways and steel, it also gave rise to one of the era's most consequential new sectors: the chemical industry. Laboratories increasingly synthesized a wide range of organic chemicals—used in pharmaceuticals, dyes, explosives, fertilizers, insecticides, pesticides, paints, plastics, synthetic rubber, fibers—rather than deriving them from natural sources. The fusion of scientific research and industrial manufacturing positioned the chemical sector at the center of industrialization.

As with boilers in the First Industrial Revolution, these new technologies created a pressing need for safety standards, in this case to manage the pervasive negative externality of pollution.

By the latter half of the nineteenth century, pollution had become a visible and widespread concern across Europe. Rapid urbanization concentrated populations in dense cities, compounding the environmental impact of coal burning, industrial waste, and inadequate treatment of sewage. Indeed, the larger the city, the greater the risk to life, with hazard ratios for mortality increasing with city size.[47] Initially, sewage pollution was a greater scourge than industrial releases in Great Britain. To delay or prevent new regulations aimed at controlling pollution, the British chemical industry offered arguments similar to those given earlier by boiler manufacturers: Controls would endanger national prosperity, would not significantly improve the quality of air and water, or would be premature until the technical situation was better understood—rationalizations that continue to resonate today. Despite these efforts, worsening river pollution, such as that produced from soda plants, finally resulted in the Alkali Act of 1863.

Similar patterns emerged elsewhere. In the Netherlands, concern initially focused on sulfuric acid and sugar residues from dye production and soon expanded to pollution from plants generating alkali and sulfuric acid as wastes. As in Great Britain, regulators turned to chemists for technical support. In Germany, the major concern was liquid emissions into lakes, rivers, and streams, such as the arsenic produced by the production of dyes. Industrialists there went a step further, claiming rivers were "natural sewage canals," a rationale that framed pollution as an efficient, not a harmful, by-product of industrial progress.[48]

These developments marked the start of a new type of safety standards, prompted not only by concerns about human health, but also by wider understanding of negative externalities resulting from the expanding ecological footprint of industrial production and growing levels of consumption. Quality standards mattered for the quality of life, the deeper fundamental goal of development. Chapter 6 examines the resulting rise of environmental standards.

Food

Standards for food safety began to emerge in the medieval period. In medieval Islamic societies, the *Muhtasib* (market inspector) played a pivotal role in enforcing norms relating to safety and quality. Beyond policing fair trade, the *Muhtasib* regulated food production, barred the sick from working in food-related trades, and supervised sanitation in urban settings, highlighting an early institutional framework for public health.[49]

The Industrial Revolutions and rapid urbanization meant that people increasingly purchased the food they consumed rather than growing it themselves. Together with growing international trade in foodstuffs, public concern about food safety mounted, prompting many European countries to pass food laws. A number of parallel attempts were undertaken to establish common techniques for assessing food samples so that results could be compared and interpreted. A notable milestone came in 1891 when Austria initiated the Codex Alimentarius Austriacus, publishing its first standards in 1911.

In the United States, reform came from the bottom up. Public outrage over food adulteration and unsanitary conditions in factories erupted after the publication of Upton Sinclair's semi-fictionalized exposé, *The Jungle*, in 1906. Whereas earlier attempts at reform had stalled as a result of lobbying by the meat industry, Sinclair's searing descriptions led to plummeting meat sales and foreign bans on imports of meat from the United States. An additional examination by independent inspectors appointed by the government was

equally damning (and also meant that the meat industry could not dismiss Sinclair's book as mere fiction). Together, these resulted in the Pure Food and Drug Act and the Federal Meat Inspection Act (both passed in 1906), the first comprehensive federal laws regarding food safety in the United States. These laws laid the groundwork for future regulations, culminating in the 1938 Federal Food, Drug, and Cosmetic Act.[50]

In Europe, the Codex Alimentarius Austriacus metamorphosed into the Codex Alimentarius Europaeus, which developed standardized rules for testing food samples to eliminate trade barriers within the region. It subsequently joined forces with the Food and Agriculture Organization and the World Health Organization (WHO) to ensure common global standards for food safety to prevent barriers to food trade. Since 1963, the Codex Commission of these two organizations has been issuing its Codex Alimentarius standards to guide governments in establishing regulations pertaining to food safety. Growing government sensitivity to concerns surrounding food safety prompted the incorporation of sanitary and phytosanitary measures into the framework of the World Trade Organization. Yet as some countries adopt increasingly stringent standards for food safety, it remains unclear to what degree these measures primarily reflect scientific evidence, domestic consumer preferences, or a veiled form of protectionism.

Compatibility standards

The foundational compatibility standard: The communication tools of script and language

Script standardization has evolved from a tool of resource management and state control to a technical protocol for global interoperability.[51] Early societies found standardization of script and language critical for communication, recordkeeping, and institutional interactions. It would also be an early forerunner of the power of network externalities. The development of cuneiform in Mesopotamia (c. 3100 BCE) exemplifies this pattern, evolving from pictographs to a standardized system encoding complex texts. Thousands of surviving clay tablets reveal its primary economic function: tracking goods, labor, and transactions to support centralized governance and long-distance trade.[52] Similarly, Egypt's Middle Kingdom (c. 2000 BCE) institutionalized hieratic script—a cursive derivative of hieroglyphs—to streamline taxation, legal documentation, and resource allocation, reflecting state-driven standardization to promote administrative efficiency.[53] These systems developed symbiotically: Writing enabled management of resources on a large scale, and state demands shaped script uniformity.[54] The Phoenician alphabet (c. 1000 BCE) further revolutionized compatibility by introducing a simplified, phonetically consistent script that laid the groundwork for later alphabets, including those for Greek and Latin.

Communication compatibility did not always require written language. The Inca Empire (1450–1534 CE), lacking a writing system, employed *khipu*—a standardized knotted-cord system—to manage census data, taxation, and resource distribution across 12 million subjects. Trained personnel (*khipukamayuqs*) ensured consistent interpretation.[55]

Script standardization accelerated during the medieval era in Europe, driven by technological innovation and geopolitical imperatives. The invention of the printing press by Johannes Gutenberg (c. 1440) necessitated uniform letterforms, entrenching Roman and Gothic scripts across Europe. Market expansion solidified the Latin alphabet as a de facto standard, reinforcing its dominance in administrative and scholarly contexts.[56] By the twentieth century, script modernization became a tool for cultural and economic alignment: In 1928, Turkey adopted a Latin-based

alphabet under Atatürk, replacing the previous Arabic script, to boost literacy, streamline bureaucracy, and integrate with the industrializing West, demonstrating the effects of choosing a specific standard.[57]

The network effects of standardization in languages came at a cost to languages spoken by linguistic minorities, underlying the inherent tension between compatibility standards and diversity. About 43 percent of the more than 7,000 languages in the world are endangered and likely to die off by the end of this century, the United Nations Educational, Scientific and Cultural Organization (UNESCO) estimates. The power of standardization has led to larger numbers of people speaking fewer languages as glottophagy—a dominant language's consuming smaller ones—has become more common. More than half of the world's population speaks just 23 languages. This matters critically, as language and cultural diversity appear to correlate with regional biodiversity: Loss of one may endanger the other.

The need for new standardized scripts driven by novel technologies emerged during the Second and Third Industrial Revolutions. The telegraph's true value could be realized only when it could bridge geographic and linguistic divides, which required a standardized script: Morse code. The dawn of the computer age necessitated the American Standard Code for Information Interchange, better known as ASCII. This character-encoding system, released in 1963, digitized the Latin alphabet, numerals, and symbols, enabling seamless data exchange across early computer networks. Its Anglo-centric limitations spurred Unicode (1991), standardizing more than 149,000 characters across global scripts (Cyrillic to Han ideographs) to ensure cross-linguistic digital compatibility. Barcodes—including quick-response or QR codes—similarly provide universal standardized "scripts" in the form of standardized, machine-readable formats that enable data to be captured efficiently and ensure interoperability across systems.

The Second Industrial Revolution: The age of standards and the emergence of complex networks and systems and standardization organizations

The Second Industrial Revolution, which unfolded between the final third of the nineteenth century and the beginning of the First World War, marked the onset of the "age of standards." The deployment of large technical networks such as electricity and railways, mass production based on a system of interchangeable parts, and pressures to protect workers and consumers (such as those in the field of food adulteration) fueled a powerful movement led by engineering associations, hygienists, major corporations, and governments. Beginning with the creation of the German Reichsanstalt in 1887, countries began establishing national standardization offices. The first international organization for standardization, the International Electrotechnical Commission (IEC), established in 1906, signaled the increasing international prominence of standards at the dawn of the twentieth century.

The deepening connection between scientific progress and technological development in part defined this era. As David Noble (1977, 76) observed, "scientific standardization paved the way for industrial standardization." Scientific inquiry demanded standardized vocabularies and measurement systems, leading to classification schemes such as the periodic table and the Linnaean taxonomy. Breakthroughs in chemistry and burgeoning new chemical industries, from dyestuffs to refining, led to the Geneva Rules for chemical nomenclature in 1892. Over several decades (and as a result of many international conferences), these efforts led to the emergence of the International Union of Pure and Applied Chemistry (IUPAC), which coordinated the international standardization of nomenclature, terminology, symbols, and quantities in chemistry. Electropedia, produced by the IEC and first

published in 1938, presented international standards in electrotechnology, the world's most comprehensive database of terminology, containing more than 22,000 terms in two dozen languages.

Later, the United Nations system began managing some classification schemes. For instance, its Globally Harmonized System of Classification and Labelling of Chemicals standardized hazard communications, while the International Classification of Diseases (maintained and updated by WHO) enabled public health systems worldwide to categorize and share epidemiological data using a common language for diagnostics. WHO's Anatomical Therapeutic Chemical classification system and the International Nonproprietary Names system for pharmaceuticals similarly supported the global harmonization of drug nomenclature.

A distinctive hallmark of the Second Industrial Revolution was the onset of mass manufacturing. Modern manufacturing would be unthinkable without interchangeable parts, which make it possible for complex products to be assembled from mass-produced individual components. No complex product epitomized this era as much as the automobile. Although powered by a general-purpose technology, the internal combustion engine, it required a chassis, wheels, tires, brakes, brake linings, spark plugs, a carburetor, a radiator, a differential, a steering wheel, headlights, and fuel distributors (for gasoline or diesel fuel), each of which had to be built to very specific standards to enable assembly of a safe, reliable product.

The emergence of complex technologies with large network externalities (like rail, telephones, and electricity), as well as of the core infrastructures of cities (water, sewage, and gas systems), was the other defining feature of this era. These technologies required networks of closely interconnected, compatible inventions, which had to be integrated seamlessly to be effective. Whereas earlier technologies consisted of separate components that could be optimized individually, the increasingly complex technologies of this era "required a great deal of coordination that free markets did not always find easy to supply," requiring governments or other mechanisms to standardize railroad gauges, electricity voltages, rules of the road, and so on.[58] Coordination of technological systems required "technical standards," also known as "compatibility" or "interface" standards,[59] to ensure compatibility and interoperability among a system's components.

Technologies of this era not only birthed new products but also integrated global markets through innovations in transport and communication. Telegraphy, telephony, and wireless radio revolutionized global connectivity. Each evolved through networks of compatibility standards that enhanced reliability, interoperability, and cost-efficiency. But these very features would also sow the seeds for entrenching market power.

Telegrams, telephones, and trains: Shoring up hard infrastructure with the soft infrastructure of standards

The standardization of telegraphy illustrates the interplay of technological innovation, imperial ambition and control, and institutional development. Great Britain's reliance on telegraphy as a "quintessential technology of empire" drove significant advancements in cable technology and electrical measurement.[60] British physicists, in collaboration with telegraph operators, conducted pioneering research on signal propagation through underwater cables, addressing the practical challenges of imperial communication. Despite competing measures, such as Werner von Siemens's German standard, the ohm became a global de facto standard measure of electrical resistance because of Great Britain's dominance in the telegraph industry and its extensive submarine cable network, referred to as the "nerves of empire."[61] The effort to standardize the measure of electrical resistance laid the groundwork for

broader international cooperation, as subsequent electrical congresses in Paris (1881), Frankfurt (1891), and Chicago (1893) sought to harmonize electrical units and practices. These meetings culminated in the formation of the IEC in 1906, institutionalizing multilateral efforts to develop standards for a new technology. A century and a half later, the physical arteries of a successor technology, the internet—a million and a half kilometers of fiber-optic cables—crisscrossed the world's oceans, built to standards specified by the IEC and the International Telecommunication Union (ITU), two of the oldest international standards development organizations.[62]

In the United States, telegraph development followed a market-led path, shaped by competition and the federal government's decision not to acquire Samuel Morse's patents, leaving the industry to develop through private investment. This resulted in rapid growth of telegraphy but fragmented infrastructure for it. Competing firms built overlapping systems with incompatible practices until Western Union consolidated the sector through a series of mergers and acquisitions ending in 1866.[63] It imposed internal standards for operations and cemented American Morse code domestically, even as International Morse code, adopted by the International Telegraph Union in 1865, spread globally, reflecting the difficulties of reconciling national and international standardization.

Telephones were also standardized through a mix of entrepreneurial initiative, monopolistic consolidation, and eventual regulatory oversight. In the 1880s, telephone technology was in its infancy, with no formal standards; decentralized entrepreneurs operated early networks, licensed under Bell Telephone patents, and built isolated systems with little interoperability.[64] As with the telegraph, industry consolidation resulted in a single private actor driving standardization of telephony: the American Bell Telephone Company (later the American Telephone and Telegraph Company, widely known as AT&T, and even later, Verizon). Bell leveraged standardization to consolidate manufacturing and engineering across regions, creating hierarchical control that bolstered competitive advantage.[65] To mitigate resistance from local operating companies, it adopted a collaborative approach through the National Telephone Exchange Association (NTEA), through which engineers from Bell and independent companies shared operational insights to develop voluntary technical specifications adaptable to local conditions.[66] This cooperative yet strategic process laid the groundwork for interoperability while preserving Bell's influence.

The expiration of Bell's patents in the area of telephony in 1894 spurred competition, but AT&T responded with its "one system, one policy, universal service" strategy, framing monopoly control as essential for national integration. But under the guise of public benefit, positioning AT&T as a "benevolent monopoly," this rhetoric masked a strategic bid to eliminate competition.[67] By the 1910s, AT&T had absorbed most of its competitors, exerting technical and commercial control through its subsidiaries. In the 1920s, AT&T shifted tactics, engaging with national standards bodies like the American Standards Association. Although initially wary of ceding control, it recognized the strategic value of consensus committees for resolving systemic challenges, such as specifications for wooden telephone poles and radio interference, that no single firm could solve alone, while retaining dominance in critical areas like network architecture.[68]

However, in 1956, the Federal Communications Commission forced settlements in antitrust cases that mandated patent licensing and restricted AT&T to regulated services.[69] By the 1960s, rulings by the commission had dismantled AT&T's control over customer equipment, mandating standards for new technologies like modems and fostering competition in data communications. Policies based on these rulings decentralized innovation, shifting authority to industry committees and rival firms, creating demand for interoperability driven by market forces.

Another industry, railroads, exemplified the need for compatibility standards. Even a modest railway comprised hundreds of interdependent parts: couplers, brakes, rails, signals, crossties, and rolling stock. In the late nineteenth century, railroads embraced the systematic gains that professional engineers promised them by standardizing each component—from rail strength to paint colors to unit measures like "ton-miles" for cargo—to increase productivity, "precisely because they restricted the realm of technical possibilities and pursued one grand objective with single-minded purpose . . . laying down clear ground rules about operations and shunning innovations that threatened to disrupt those rules."[70]

The shift from iron to steel rails in the late nineteenth century marked a leap in productivity, enabling heavier locomotives and larger freight loads while reducing maintenance costs. Early steel rails often failed under stress as a result of inconsistent metallurgy. In response, scientists and engineers formed the American Society for Testing and Materials (ASTM) to create standardized methods for testing. Its first standard, ASTM A1, specified requirements for the quality of steel rails. These requirements significantly reduced rail failures and supported the safe operation of heavier, faster trains. By 1910, steel rails alone accounted for the largest productivity gains in the US railroad sector, saving an estimated US$479 million annually.[71] Today, ASTM is an international organization with 13,000 plus standards, ranging from measurements for aircraft braking (from its Committee on Vehicle-Pavement Systems) to standards for biodegradable plastic (from its Committee on Plastics) and standards for infrastructure that are essential to the world's built environment (from its Committee on Soil and Rock).

Railways also emerged as the quintessential example of the importance of interoperability standards, stemming from a seemingly simple technical problem: differences in railway gauges, the width between rails (refer to box 1.2). The standardization of railway gauges and steel rails thus reveals a recurring pattern in the history of compatibility standards: economic imperatives driving institutional coordination, which in turn fosters technological innovation and market integration. It also demonstrates how an industry frustrated by the unpredictability of the market-based system for patents circumvented that system by creating trade associations and engineering societies to facilitate the industrywide exchange of technical standards.

Box 1.2 The transaction costs of incompatible railway gauges

The railway "gold rush" of the nineteenth century produced a global patchwork of more than two dozen rail gauges shaped by local needs and engineering preferences. By the 1860s, the United States alone had nine distinct regions with different rail gauges; eastern Canada added a tenth. The expansion of interregional trade made the economic costs of these incompatibilities untenable. Perishable goods, in particular, suffered from delays at gauge breaks.[a] By the 1880s, competitive pressures and network consolidation pushed US railroads toward convergence around the standard gauge of four feet, eight-and-a-half inches, already prevalent in the industrial Northeast and Midwest. In a concerted effort in 1886, southern railroads converted 13,000 miles of track to standard gauge in just two days, dramatically ratcheting up the shift. This physically integrated the South into the national rail system. However, although the change spurred a shift in freight volume from steamships to

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Box 1.2 The transaction costs of incompatible railway gauges *(continued)*

rail, it did not lower prices, likely because the same collusion that enabled the gauge change also dulled its competitive effects.[b]

Although standard gauge has since become dominant within many countries, cross-border incompatibilities persist. In Eastern Europe, Ukraine and the Baltic states are increasingly developing standard-gauge (1,435 millimeters) rail connections alongside their existing broad-gauge (1,520 millimeters) infrastructure to enhance interoperability with the European Union rail system. Across the vast Eurasian landmass, freight trains from China must currently switch gauges at the Kazakh and Mongolian borders. These trains must then switch gauges again in Poland.

Decisions about gauge conversion are often framed around capital costs or engineering feasibility. Yet the deeper economic rationale lies in coordination failures, fragmented supply chains, and long-term transaction costs. Break-of-gauge points delay transit, raise handling costs, and require complex infrastructure like transfer stations. Moreover, declining global demand for legacy-gauge equipment drives up maintenance costs and creates dependency on a shrinking group of specialized suppliers, introducing risks of delay.

As countries consider whether to align their rail systems with regional standards, they must view the economics of gauge conversion not only in terms of up-front costs, but also through the lens of transaction costs, resilience of supply chains, and long-term integration.

Source: Binyam Reja and Matthias Plavec, Transport Global Unit, Infrastructure Vice Presidency, World Bank.

a. Puffert (2000).
b. Gross (2020).

The advent of mass manufacturing: Compatibility standards as coordination mechanisms

The coordinating role of standards has deep historical roots, evolving from early state oversight to market mechanisms to sophisticated regulation by industry. In ancient China, state-led efforts standardized axle lengths for wheeled vehicles, ensuring smoother travel on rutted roads, a practical solution to a widespread infrastructural challenge.[72] China also pioneered interchangeable parts in military applications such as crossbow triggers, predating similar Western developments by centuries.

The Industrial Revolutions catalyzed a paradigm shift toward technical standardization driven by the imperatives of mass production and mechanized efficiency. Interchangeable parts in modern manufacturing can be traced back to late-eighteenth-century French armories. The idea crossed the Atlantic in the early 1800s, as US armories adopted jigs, gauges, and rigorous protocols for inspection to produce standardized muskets, laying the groundwork for what became known as the "American system of manufacturing." Yet achieving seamless interchangeability remained elusive. Even after the Civil War, firms like Singer still relied on hand-fitting and serializing parts, illustrating how slowly artisanal practices retreated.[73]

True interchangeability required not only precision machine tools, but also institutional support for codifying processes. Innovations in these areas spread globally, but high costs kept interchangeability out of reach for many industries until the late nineteenth century. The turning point came with Henry Ford's synthesis of armory practices, pressed steel parts, and moving assembly lines in the 1910s. Ford's system required absolute interchangeability, achieved through specialized machine tools and strict standardization, fusing precision and scale.[74] Yet broader industrial coordination lagged. The Society of Automotive Engineers (SAE), founded in 1905, emerged to address proliferating variations in parts—such as more than 1,100 types of lock washers and tubing—by establishing industrywide standards. Its efforts at such standardization enabled smaller manufacturers to compete through economies of scale, though giants like Ford and General Motors initially made proprietary systems a priority over collaboration. This trajectory underscores the tension between market-led standardization, driven by efficiency and competition, and the systemic coordination required to mitigate the costs of fragmentation. The latter has sometimes required the "fostering hand" of the state, as seen in the "simplification" drives engineered by Herbert Hoover in the United States in the 1920s (discussed in box 1.3).

Standardization enabled mass production by codifying best practices for repeatable processes, lowering costs, and enabling learning-by-doing effects captured in Wright's Law (first observed in aircraft production in the 1930s): As cumulative production increases, unit costs decline. However, maintaining consistent quality as production increases becomes more difficult, making standards essential. They structure worker training, support process innovation, and facilitate knowledge transfer.

The production of penicillin offers a compelling case. Though discovered by Alexander Fleming in 1928, the antibiotic remained a laboratory curiosity for more than a decade. But World War II created an urgent demand for an effective antibacterial treatment, leading governments, scientists, and industry to find ways to produce penicillin on an industrial scale. Standard procedures were developed to screen, identify, and select high-yielding strains of the fungus that produces penicillin. A global effort—including notable work by US Department of Agriculture (USDA) laboratories in Peoria, Illinois—standardized how strains were tested and preserved, ensuring consistent performance in different setups for the fermentation process involved. Scaling up production across multiple facilities (especially for wartime production) required standardizing conditions for fermentation (temperature, pH, aeration, agitation), protocols for sterilization, compositions of nutrient media for growing cultures, and procedures for inoculation. After early batches of the drug were found to vary widely in potency and purity, standards for testing bioactivity and purity were set to ensure patient safety and make dosing consistent and predictable. Finally, bioreactor design was standardized with regard to dimensions, materials, and operating features, which ensured that process parameters developed in one facility could be replicated elsewhere.[75]

Standardization also began to transform commodity markets in the late nineteenth century, as exemplified by the Chicago Board of Trade's system for grading grain. By creating uniform benchmarks for quality, the board transformed grain into a fungible commodity. This decoupled ownership from physical stock, enabled trading in grain futures, and mirrored emerging practices in industry.[76]

Box 1.3 Standardization as simplification—and as an instrument of industrial policy

The rise of the United States as the global leader in manufacturing by the mid-twentieth century is often attributed to entrepreneurs like Henry Ford, whose model of mass production of automobiles set benchmarks worldwide. However, supplementing this visible hand of entrepreneurs was the fostering hand of government through its "simplification" programs, which began as a way to persuade manufacturers to move to standard sizes, thereby pushing manufacturers toward mass production.

Standard sizes—for example, of beds, printer paper, and electrical outlets—are a familiar feature of modern production and consumption that are often taken for granted. What makes a nation's standard sizes "standard" is that dozens, if not hundreds, of firms manufacture everyday products in the same, limited set of sizes or shapes.

In the early twentieth century, standard sizes in the United States were confined almost entirely within individual firms. Even the Ford Motor Company, initially a small-scale assembler of automobiles, adhered to the prevailing strategy, until it took the radical step of abruptly cutting its product line to a single model and ramping up production. Instead of catering to consumer demand, it "worked out a car and at a price which would meet the largest average need. In effect, [it] standardized the customer."[a]

The fragmentation that prevailed at the time was in part the outgrowth of a bewildering number of state and national laws. A 1912 compendium on laws governing weights and measures totaled 564 pages, and codes governing food regulation and buildings differed from the national through the state to the municipal level.[b] At the beginning of the 1920s, US manufacturers made mattresses and beds, for example, in 78 sizes; within a decade, 90 percent of the industry's output conformed to 4 standard sizes. This remarkable convergence raises two questions: How did it happen? What were the consequences?

The effort originated during World War I, when the US government sought to conserve critical resources—labor, materials, and transportation—by persuading civilian manufacturers to reduce the variety of goods they produced. Working through trade associations, the government helped industries reach consensus on conservation measures.[c] Initially, it encouraged compliance through social pressure and public pledges, reinforcing it later by giving firms priority in the allocation of resources. Within 18 months, product variety shrank across about 250 business lines.

When the war ended, the government dismantled the office that had coordinated simplification. But momentum revived in 1921 when the Federated American Engineering Societies,

(Box continues next page)

Box 1.3 Standardization as simplification—and as an instrument of industrial policy *(continued)*

led by Herbert Hoover, issued *Waste in Industry*. This report argued that raising the national standard of living hinged on enhancing "national productivity," which required eliminating waste in industry.[d] When Hoover became Secretary of Commerce, he created the Division of Simplified Practice within the National Bureau of Standards to act as an "unbiased third party," helping industries reach voluntary "simplification" agreements to reduce product variety and promote mass production.[e]

The first simplification efforts, focused on paving bricks, mattresses, and bedsprings, reduced varieties of these goods by more than 90 percent. By the early 1930s, 135 Simplified Practice Recommendations were in effect. Though adoption slowed during the Great Depression, the number of these recommendations rose to 173 by 1939 and to 267 by 1971.

National-level agreements do not arise spontaneously; they must be constructed.[f] Simplification succeeded because it followed a voluntary, data-driven approach. Without legal powers of enforcement, the government relied on social incentives and procedural legitimacy to maximize consensus as a means of enhancing adherence. The endeavor succeeded because of efforts mounted on three fronts. The first was winning consumer acceptance through advertising campaigns that resulted in firms' "catering to the tastes and needs of the average buyer, leaving those who fall outside their field of specialization to the special-order manufacturer."[g] The second was leveraging the power of government procurement, ensuring that only products that met the federal specifications in Simplified Practice Recommendations could be sold to the federal government, the nation's largest consumer. The third was building alliances between the National Bureau of Standards and other federal agencies as well as private associations with high credibility in the private sector: the US Chamber of Commerce and the American Engineering Standards Committee (AESC, now the American National Standards Institute, ANSI).

Overall, standardization, in the guise of simplification coordinated by the federal government, played an important role in the rise of mass production and consumption in the United States, shaping American manufacturing for decades. One observer described it as "an industrial policy of first-rate importance and one which can scarcely be ignored."[h] With the return of industrial policy today, the role of standards should not be underestimated, either.

Source: Dunlavy 2025.

a. Couzens (1921, 263–64).
b. Gephart (1919, 265); Whitehorne (1923, 40).
c. Werking (1978).
d. FAES (1921, ix); Hoover (1921, 77).
e. Feiker (1922); Hoover (1922); Priest (1926).
f. Offe and Wiesenthal (1980); Olson (1965).
g. Bangs (1930, 234).
h. Chisholm (1922).

The evolution of standards following World War II

The international system changed markedly following World War II. For the purposes of this Report, four developments radically changed the world of standards. First, a range of new international organizations, including the Bretton Woods institutions (the International Monetary Fund and the World Bank), the International Labour Organization (ILO), and WHO were established to manage the international order following the war. Although intergovernmental organizations for developing standards had emerged in the nineteenth century, notably the International Telegraph Union (1865, subsequently ITU) and the Universal Postal Union (1874), standards development remained largely within national standards bodies. The establishment of the International Organization for Standardization (ISO) in 1947 complemented the founding of the IEC, a pioneer in the field, in 1906. Other international organizations also became involved in the development of standards in their domains, such as health (WHO) and labor (ILO), through conventions.

A second development was the emergence of many new states following waves of decolonization between 1945 and 1960 (three dozen new states in Africa and Asia alone), followed by another 92 new states thereafter. These newly independent countries had nation building as a central objective. Standards were an important instrument for achieving this, as illustrated by the case study on India discussed in box 1.1, although not all new states pursued a national strategy for standardization.

Third, global economic integration deepened as a result of increasing cross-border movement of goods (especially manufactured goods), people (migration), and money (financial flows). Development of standards lubricated these booming flows, providing the "soft infrastructure" underpinning the flows.

The fourth development was technological: the Third Industrial Revolution, a digital transformation powered by semiconductors and information technology. This revolution ushered in an era of rapid innovation in digital products and services, underpinned by the development of seamless compatibility standards and protocols for communication (refer to chapter 4). It further accelerated globalization, especially after the 1990s, this time in digital services. But as with all transformative technologies, it also brought with it new risks. Managing them would require new standards.

Although each of these trends independently shaped the world of standards, their interactive effects resulted in a more overarching trend: a world of greater complexity that could be managed only through more standards.

Compatibility standards for cross-border flows of people and goods

The primary document for international travel, the passport, regulates international movement while literally putting a stamp on nationality. Before World War I, international travel usually did not require a passport, though practices varied by country. This changed after the Great War, as nationalism surged. The League of Nations convened a series of passport conferences in the 1920s with the aim of abolishing requirements for passports. Although it soon abandoned that goal, its efforts in this area produced the first international standards for passports, with the British passport becoming the model for national designs.[77]

As air traffic increased, so did the need for harmonized formats for passports to expedite passenger processing. The United Nations' creation of the International Civil Aviation Organization (ICAO) in 1944 marked a turning point. One of the organization's mandates was to standardize travel documents, particularly to facilitate air travel.

In 1968, ICAO convened a small group of experts to develop a machine-readable zone on passports,

focusing on document security and proof of citizenship. However, the initial format failed to accommodate African, Arabic, and Asian names, the use of scripts other than Roman, and diacritics such as accent marks. Eventually, the first edition of the standard for the zone was published in 1980 and was accepted as an ISO standard, smoothing the rapid growth of international air traffic, from 0.2 billion passengers in 1980 to 1.9 billion by 2019.[78]

Subsequently, efforts mounted to standardize the format of visas affixed to passport pages, which finally occurred in 1992.[79] Later, the standard for the layout of passport data was modified to accommodate the European Union's Schengen visa. As concerns regarding international security mounted, new biometric standards were included, starting with facial recognition; fingerprint and iris recognition were later added as additional supporting technologies. After the 9/11 terrorist attacks in 2001, the United States required countries in its Visa Waiver Program to issue biometric passports aligned with ICAO's new electronic machine-readable travel document (eMRTD) standard. Standards for documentation for international travel further evolved with e-Passports, which incorporate a contactless radio-frequency identification chip (using near-field communication protocols) that securely stores digitally signed personal and biometric data in line with ICAO specifications. Although the eMRTD standard would likely have been widely adopted over time regardless, changing perceptions of risk precipitated political pressures on countries to adopt it more rapidly.

Indeed, the ICAO 9303 MRTD/eMRTD standard proved so successful that it became a de facto standard for national ID cards in many jurisdictions, including most member countries of the European Union and European Economic Area, as well as Albania, Algeria, Brazil, the Kyrgyz Republic, Pakistan, Panama, Saudi Arabia, Ukraine, and Uruguay, among others, where these documents can be read using the same equipment as passports. The biometric chip included on these ID cards has proven very useful as the digital economy has grown, because it allows a form of digital ID authentication using biometric data.

A different process of developing compatible standards led to the massive growth of global trade in goods (which has increased about 45-fold in the last 75 years). Foremost was the land-sea shipping of dry goods general (or "break-bulk") cargo using standardized containers (refer to box 1.4).

The massive increases in air passenger traffic and seaborne goods traffic catalyzed by standardizing the passport and containers in turn created an urgent need for a new set of safety standards for each. Standards put into place by ICAO and the International Air Transport Association (IATA) drastically reduced the risk of a fatality in commercial air travel from 1 per every 350,000 passenger boardings in 1968–77 to 1 per every 13.7 million boardings globally in 2018–22. Over this half century, air travel fatalities dropped about 7 percent annually and by a factor of two every decade.[80]

The history of marine safety, it has been said, "is soaked in water and written in blood."[81] As with the development of most other safety standards, major disasters have largely driven the process in the case of marine safety. The sinking of the "unsinkable" *Titanic* in 1912 was the defining moment in modern maritime safety, leading to the adoption of the International Convention for the Safety of Life at Sea in 1914. One ship in every 100 was lost in 1910. A century later, this rate had declined to about 1 ship in every 670,[82] the result of a host of safety standards put into place by an evolving system of marine insurance and technical standards established by Lloyd's Register of Shipping and later expanded by the Inter-Governmental Maritime Consultative Organization as an arm of the United Nations in 1948 (the latter in turn became the International Maritime Organization, or IMO, in 1959).

Box 1.4 A box on a box

The standardized intermodal shipping container represents one of modern economic history's most transformative yet understated innovations. This seemingly simple steel box, leveraging standardization and intermodality, eliminated critical bottlenecks in shipping goods using a combination of land and sea transport; unlocked unprecedented economies of scale; and revolutionized the cost, speed, and geographic span of global transport of freight.

Until the mid-twentieth century, the technology for unloading general cargo through break-bulk shipping had barely changed for centuries. A labor-intensive process involved manually handling individual items in barrels, sacks, and crates, which were transferred piecemeal between land and ship. Despite minor improvements like pallets, cargo handling remained inefficient, making the risk of loss or damage high and causing port congestion and delays, with ships spending two-thirds of their productive time idle in port, loading or unloading.

Italian visionary Silvio Crespi, founding director of the Bureau International des Containers et du Transport Intermodal [International Bureau of Containers and Intermodal Transport], conceptualized the modern container as early as 1928, describing it as "the mobile box of the carriage." It would be detachable from wheels and platform, enabling "international house-to-house transport via multiple modes of transport" in which "reloading is kept to a minimum, and the goods within the container are not touched at all."[a] But realizing this vision would require systemic change.

The breakthrough came from outside shipping. Concerned about highway congestion, US trucking entrepreneur Malcom McLean envisioned integrating trucking and shipping door to door. His pivotal insight was that success in this type of integration required complementary innovations across the entire chain: ships, cranes, ports, trucks, trains, and storage. He shipped the first intermodal containers on a converted tanker in 1956.

Initially, containerization expanded domestically within the United States. Loading costs plummeted from US$5.83 per ton for break bulk to a mere US$0.16 per ton for containers: a 36-fold reduction. The time savings, which were also dramatic, meant that ships spent vastly less time idle in port, aligning with McLean's principle that "a ship earns money only when she's at sea."

But early adoption faced significant hurdles. Container sizes varied widely, creating incompatibility. Manufacturers, haulers, forwarders, agents, railways, and stevedoring companies operated in isolation, using diverse handling practices and equipment, hindering interoperability. The US Federal Maritime Board initially drove standardization, mandating in 1961 that ships for commercial transport be built to specific dimensions in order to receive

(Box continues next page)

Box 1.4 A box on a box *(continued)*

construction subsidies. But international diffusion of standards accelerated only following McLean's decision to license key patents royalty free to the International Organization for Standardization (ISO), which went on to create standards for almost every aspect of containers (in 1965)—from their dimensions, to how they can be stacked, to the twist locks that securely fasten them to ships' decks or to trucks, to their strength requirements and lifting standards—making a universal system feasible. Although adoption was rapid, usage was more gradual, partly because of the sizable fixed costs of investment.[b]

Dockworkers resisted the implementation of containerization, rightly viewing it as a threat to their livelihoods, as did port authorities navigating the trade-offs between significant up-front costs and uncertain returns. Initially, smaller ports that undertook the necessary investments edged out then-dominant ports. Soon, containerization sharply reduced the costs of handling cargo, insurance premiums, and inventory capital tied up in transit. Transit time between Australia and Europe, for instance, dropped from 70 to 34 days, halving the associated capital cost of inventory. The reduction in ship turnaround times unlocked large economies of scale. Vessel capacity quadrupled between the 1960s and the 1980s, only to increase even further in the decades that followed. Sealed containers drastically reduced the pilferage, damage, and theft common in break-bulk shipping, reducing insurance costs greatly. By 1983, nearly 90 percent of countries had container ports, underscoring the rapid and pervasive adoption of containerized shipping.

The private sector developed the shipping container, but the container had its global impact only after ISO developed a standard format for it. The standardization of the physical container itself, however, was not enough. A complementary standardization was needed in the procedures and information flows that accompany containerized trade. The United Nations Centre for Trade Facilitation and Electronic Business (UN/CEFACT) played a key role in developing procedural standards and standards for data exchange that enabled efficient container use across borders and transport modes.

Containerization delivered "a permanent boost" to bilateral trade, with a cumulative increase of 1,240 percent in trade among developed countries after 15 years, far exceeding the impacts of trade policy.[c] Arguably, it "boosted globalisation more than all trade agreements in the past 50 years put together."[d]

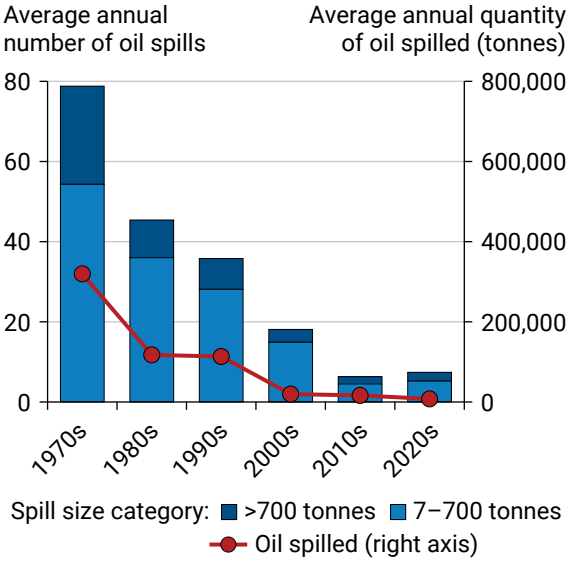
Source: WDR 2025 team.

a. Klose (2015, 47).
b. Egyedi (2000); Rua (2014).
c. Bernhofen et al. (2016).
d. *Economist* (2013).

Although ship disasters for the most part meant loss of lives and financial costs, one type of ship disaster also had substantial negative externalities as a result of the environmental damage that resulted: oil spills from oil tankers. As global demand for oil grew in the post–World War II era, so did the number and size of oil tankers—and the number of environmental disasters from oil spills. The *Torrey Canyon* oil spill off the French and Cornish coasts in 1967 resulted in the landmark International Convention for the Prevention of Pollution from Ships. Although this convention was adopted in 1973, it became effective only in 1983, 16 years after the disaster. A series of other major disasters involving oil tankers, including the *Amoco Cadiz* in 1978 (off the Brittany coast in France) and *Exxon Valdez* in 1989 (off the coast of Alaska), increased pressure to raise standards for shipping oil, encompassing construction (double hulls), crew certification and staffing, contingency planning, and the development of plans for responding to disasters. US regulators made the ceiling for compensation in cases of accidents so high that the tanker industry mobilized, resulting in a 90 percent decline in oil spills over the past half century (refer to figure 1.2).

Figure 1.2 Standardization, in the form of improved oil tanker design and protocols, and regulation have sharply decreased the size and number of oil spills since 1970

Global spills from oil tankers, by decade



Source: Oil Tanker Spill Statistics 2024 (web page), International Tanker Owners Pollution Federation, https://www.itopf.org/knowledge-resources/data-statistics/oil-tanker-spill-statistics-2024/.

Note: The bars show the average number of spills annually in each decade (left axis) broken down by spill size category. The plotted red line shows the average annual quantity spilled (right axis).

Interoperability standards as protocols in the digital age

Information and communications technologies have been the core technological drivers of the Third Industrial Revolution. They have been built on multiple layers of countless standards for computer hardware and software and for the internet and wireless networks. As innovation has accelerated, standards have proliferated across competing firms, consortia, and nations, becoming increasingly salient in geopolitical technology-centered competition. Macro-level standards for infrastructure (such as fiber-optic specifications from ITU and space-data interfaces from the Consultative Committee for Space Data Systems, or CCSDS) have complemented micro-level protocols (such as those for LANs, Bluetooth, USB, and wireless communications) shaped by the Institute of Electrical and Electronics Engineers (IEEE) and private consortia.

From the 1950s to the 1980s, proprietary products in the area of networking developed by dominant firms like Digital and IBM dominated computing. However, beginning in the 1970s, nonproprietary standards such as TCP/IP emerged from a Cold War–era blend of academic and defense research in noncommercial settings. Ethernet's triumph as the standard for LANs resulted not from its technical superiority to its competitor

(IBM's token ring), but because its promoters made it an open standard, allowing any firm to build products compatible with Ethernet. This created a broad technological community that contributed to ongoing development, testing, and knowledge sharing, which steadily improved Ethernet and lowered its cost.[83]

However, open standards alone do not guarantee success. In the mid-1980s, the Open Systems Interconnection (OSI) model seemed poised to become the dominant global standard in network communications. Backed by major firms like Digital, Honeywell, and IBM, it was supported by governments across Asia, Europe, and North America and became an ISO standard in 1984. Although the US government had sponsored the internet protocols, it embraced the conclusions of a 1985 National Research Council report that recommended moving toward OSI. Indeed, the Department of Commerce mandated in 1988 that all computers purchased by US government agencies employ the OSI standard.[84]

Despite the mandate, that did not happen. OSI succumbed to a fatal flaw that, ironically, stemmed from its commitment to openness. The formal rules of international standardization allowed any interested party to participate in the standards development process, resulting in clashing visions and disruptive tactics.[85] The emphasis on inclusiveness came at the expense of speed, a fatal liability in regard to rapidly evolving technologies.

By contrast, internet protocols were widely implemented during the 1980s and early 1990s because of their low cost and flexibility.[86] Interestingly for such a transformative technology, the process of creating standards for internet protocols was managed in a remarkably open, decentralized manner. Tim Berners-Lee invented the web at CERN (the European Organization for Nuclear Research) in 1989 (coining the term "World Wide Web"), and a few years later, in 1994, the World Wide Web Consortium (W3C) was established at the Massachusetts Institute of Technology (MIT, in collaboration with CERN) at the urging of many firms investing large resources in the web. Subsequently, the consortium added three other institutions (in China, Japan, and Europe) as cohosts that jointly partnered in a "hosted model," and in 2023, it transitioned into a new public-interest nonprofit organization, maintaining its core mission to develop open web standards (such as HTML, Extensible HTML [XHTML], Cascading Style Sheets [CSS], and XML). Although ITU developed key standards related to public key infrastructures, organizations such as the Internet Engineering Task Force, the European Telecommunications Standards Institute, ISO, and the IEC have all developed standards related to public key infrastructures for different contexts (refer to spotlight 5).

Despite the success of open systems, strong global network effects continued to act as incentives for proprietary standards. Microsoft's DOS and Windows, Apple's control over iOS application programming interfaces and its App Store, and Google's Android ecosystem enabled the firms that created them to dominate developers and users alike—and to extract massive rents. Still, firms have often joined standardization efforts—despite commercial rivalries—because such efforts have offered shared technological road maps, especially when firms have had complementary capabilities. Industry-driven consortia have produced many now-ubiquitous standards for interoperability such as Wi-Fi, Bluetooth, and HTML.

Standards have become even more important in areas in which there is a convergence of complex technologies, such as in the cases of 5G telecommunications networks and the Internet of Things. In the absence of a clear platform leader in a particular ecosystem, standards are key for shaping and coordinating innovation. Firms participate because participation enables them to shape technology trajectories, collaborate on joint development, and gain access to strategic information.

Currently, Werner von Siemens's assertion in the late nineteenth century that "who owns the standards, owns the market" appears to have new adherents, because technological standards have emerged as a key geopolitical battleground among the major powers. Multilateral standards development organizations, such as ITU and the World Intellectual Property Organization (WIPO) have themselves become part of a "battle of standards," especially in emerging technologies for 5G and 6G, with developing countries largely on the sidelines. If standards represented a unifying world in the twentieth century, today a fragmenting world could well result in fragmented standards putting developing countries in a quandary: How should they navigate a world of fragmented standards if competing standards emerge?

Conclusion

From ancient systems of measurement to contemporary digital protocols, the evolution of standards reflects humanity's pursuit of order, trust, and innovation through harmonized practices and risk mitigation. These attributes have been crucial for reducing the transaction costs and information asymmetries that weaken markets. Standards have long served as codified ecosystems that have been vital for the diffusion and adoption of new technologies and for enhancing public welfare.

An important lesson from history is that standards involve trade-offs. In the process of developing standards, these include inclusion versus speed or expertise versus capture. When standards are being adopted, trade-offs exist between cost and quality, scale and diversity, and innovation and technology lock-in. On the other hand, there are complementarities between development and adoption. Deeper involvement in the development of a standard enhances the likelihood that an organization will implement the standard. The next chapter explores these trade-offs.

The history of the three successive Industrial Revolutions also teaches the critical importance of standards for managing the risks that arise from new technologies. With the dawn of the Fourth Industrial Revolution and the growing maelstrom from a combination of an incredibly transformative technology (artificial intelligence), turbocharged entrepreneurs, and intensifying geopolitical rivalries, the need for standards to manage these risks has never been greater.

Notes

1. The chapter is necessarily selective, and the three broad types of standards serve as a heuristic to organize a very broad field. It is not exhaustive, and multiple categories often operate within the same place and historical periods. For a more comprehensive classification, refer to de Vries (1998).
2. Oppenheim (1954).
3. Leemans (1960).
4. Englund (1991).
5. Middeke-Conlin (2020).
6. Metrology is the scientific study of measurement, establishing a common understanding of units and traceability.
7. Perry (1955), 5.
8. Perry (1955); Willard (2008).
9. Stone (2014).
10. Vincent (2022).
11. Rottländer (1985).
12. Clark (2010).
13. Landels (2000).
14. Perry (1955).
15. Ialongo et al. (2021); Rahmstorf (2014).
16. Mederos and Lamberg-Karlovsky (2001).
17. Ialongo et al. (2021).
18. Shamasastry (1915); Sihag (2004).
19. Li (2017); Loewe (2004); Major and Cook (2017).
20. Rosenthal (1964).
21. de Vries (2025); Rosenthal (1964).
22. Epstein (1991).
23. Ogilvie (2019).
24. Ho (1962).
25. Elman (2013).
26. Bourdieu and Passeron (1977).
27. Jacob Köbel (1536), "Geometrei von Künstlichen Messen und absehen," cited in Cochrane (1966, 48).
28. Alder (1995).
29. Vincent (2022).
30. Vincent (2022).

31. Alder (2002).
32. Alder (2002); Vincent (2022).
33. Wise (1995).
34. Scott (2020).
35. Scott (2020).
36. Kula (2014).
37. Vincent (2022).
38. John (2015).
39. Quinn (2011); Vincent (2022).
40. Winchester (2018).
41. The discussion on France and Great Britain draws on Fressoz (2025), a background paper prepared for this Report. The discussion on the United States draws on Burke (1966).
42. Boiler Laws Committee (1921), 2–3.
43. UIE (2017).
44. Coffman et al. (2022).
45. Seck and Evans (2004).
46. Knowles (2011).
47. Cain and Hong (2009).
48. Homburg et al. (1998).
49. Buckley (1992); Tengku Zawawi et al. (2021).
50. Barkan (1985); Hutt and Hutt (1984).
51. Although de Vries (1998) considers scripts and alphabets to be "basic standards," in the threefold classification set out in this Report, they are included under compatibility standards.
52. Schmandt-Besserat (2009).
53. Allen (2013).
54. Vincent (2022).
55. NIST (2025); Urton (2010).
56. Eisenstein (1980).
57. Lewis (1999).
58. Mokyr (2000).
59. David and Greenstein (1990).
60. Hunt (1997).
61. Hunt (1997); Russell (2005).
62. Saran (2014).
63. Du Boff (1980); Thompson (1947).
64. Russell (2014).
65. Smith (1985).
66. Garnet (1985); Russell (2014).
67. Russell (2014).
68. Russell (2014).
69. Russell (2014).
70. Usselman (2002, 142).
71. Fishlow (1966); Usselman (2002).
72. Major and Cook (2017).
73. Hounshell (1984).
74. Hounshell (1984).
75. Bud (2007).
76. Cronon (1992).
77. Lloyd (2003).
78. Refer to "World Air Passenger Traffic Evolution, 1980–2020" (chart), International Energy Agency (sourced from the International Civil Aviation Organization), https://www.iea.org/data-and-statistics/charts/world-air-passenger-traffic-evolution-1980-2020.
79. Chatwin (2011).
80. Barnett and Reig Torra (2024).
81. Keefe (2014).
82. AGCS (2012).
83. von Burg (2002).
84. Russell (2013).
85. Russell (2013).
86. Abbate (1999).

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