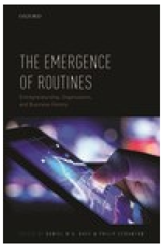

The Emergence of Routines: Entrepreneurship, Organization, and Business History
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CHAPTER

6 Heuristics, Specifications, and Routines in Building Long-Span Railway Bridges on the Western Rivers, 1865–80

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Abstract

After 1865, a new industry, uniquely American, grew to prominence making standard and semi-custom iron bridges for roads and railways. Using illustrated catalogues, specialized firms like Keystone Bridge, Phoenix Bridge, and American Bridge Company created national markets for their pin-connected bridges. With nested routines and procedures ordering the processes of design and production, they transformed bridge building from a local and empirical art into a rationalized industry. After 1870, an innovative entrepreneur, James Eads, upset established procedures at these firms. Promoting a new arched design and a new material—steel—Eads insisted on new routines in the industry. Concurrently, civil engineers and editors of technical journals advocated new approaches in design and construction to counter the problem of bridge collapses. These novel routines became instruments to force institutional and technological change among the railroads, iron and steel mills, consulting engineers, and bridge makers that built these essential structures.

Keywords: Theodore Cooper, James Eads, truss bridge, pin-connected bridge, tensile strength, Keystone Bridge Company, bridge failures

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The railroad boom that followed the American Civil War spurred the creation and growth of novel industries and new organizational arrangements among firms. This chapter explores the interactions of three kinds of companies, all collaborators in creating the new long-span iron and steel bridges sought by interregional railroads.[1] The firms came together in contractual relationships to establish short-term joint projects. First an independent financing and operating company secured charters, developed financing, and designed a bridge.[2] In 1865 those designs were often little more than sketches or verbal representations. By 1880 the operating companies typically drafted complete plans with thorough specifications. That transition, its causes, and results, is the narrative focus here. With its design needs more or less specified, the financing/operating company then turned to specialized bridge construction firms, like American Bridge or Keystone Bridge, for detailed design, site preparation, and erecting services. Those fabrication shops in turn secured iron or ↳ steel components from rolling mills. This joint-project model developed after the Civil War and continued into the twentieth century. It relied upon the creation and development of organizational routines, embodied in physical specifications for components, in materials testing practices, and in deflection testing of finished bridges. Beyond such formal routines, all three parties guided their interactions through heuristics, "the custom of the trade" as contemporaries put it.

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Students of organizational routines developed the concept to better understand how firms develop and wield their internal capacities.[3] One kind of firm discussed here, the bridge-construction companies (also known as contract shops or catalogue bridge makers), is a particularly interesting subject for theoretical and historical study because its entire *raison d'être* grew from nested routines (both explicit and tacit) that shaped its products, production methods, pricing, and markets. Before the catalogue shops, bridges had been empirical structures, typically custom built by local artisans. Through its routines, the new industry largely recast road and railway bridges as semi-standard products, rationalized by engineering and sold nationally. In its commonplace meaning, the concept of routine suggests inertia, what technological historians typically call momentum.[4] The routines examined here, however, became organizational tools to force innovation and direct it down certain paths. Nelson and Winter are mindful of the tension between routines and innovation, for they ultimately seek to craft supple models, true to historical complexity, of the ways in which firms succeed or fail as agents in Schumpeter's creative destruction.

This account complements that body of work in two ways. It examines how and why routines in bridge construction changed during a period of rapid technological innovation. My focus is on new routines and other recurring "action patterns" that shaped collaborations across three main entities: the bridge-financing/operating companies, the big contract or catalogue shops, and the iron and steel mills that supplied components. Exploring the uses and evolution of routines across firms, rather than within them, is the second contribution of this study. Moreover, these joint ventures offer insights into four larger issues:

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1. The firms engaged in these short-term projects typically bound each other by formal legal contracts. Or at least they tried to. But those documents provided only skeletal understandings of rights and duties. To actually achieve the desired outcomes—to build a bridge on budget, on time, and with desired load capacities—the parties also needed to craft frameworks for common understanding. Heuristics and routines served that function.

2. During the fifteen years treated here (1865–80), the dominant materials and design paradigms for American long-span railway bridges shifted radically, from wooden to iron trusses to experimental forms in steel. Evolving routines became the primary instrument by which design engineers and railroads forced this rapid rate of innovation on their collaborators in these joint ventures. Emergent routines stoked technological innovation.

3. The routines also became tools to alter power and responsibility. Specifically, bridge-financing corporations used routines to gain contractual power over bridge builders. Builders in turn increased their own reach by imposing clear routines on their suppliers of iron and steel.

4. Bridge failures were all too common in the era. That bland term of engineering art encompassed a range of mayhem: superstructures that fell during erection, piers or abutments undermined by river currents, and—most catastrophically—loaded trains that overwhelmed an outwardly safe span and plunged at speed into the river below. Apparently, routines also became a tool by which the three parties that made long-span bridges attempted to hold off liability claims by outside parties.

Before exploring these developments in detail, this chapter gives a short history of long-span bridges from 1865 to 1880. Then it reviews the methods wielded by engineers and bridge builders circa 1865 to understand the strengths of materials and the capacities of their common truss forms. It next describes the new catalogue bridge industry that began to meet the postbellum bridging needs of towns and railways. Next it outlines how James B. Eads and his design team at St. Louis created new routines to guide the interaction of his St. Louis Bridge Company with its lead contractor, Keystone Bridge Company of Pittsburgh, and Keystone's subcontractor, the William Butcher Steel Works of Philadelphia. Then we turn to selected other bridging projects across the 1870s, considering particularly the roles of failure and the actions of outside parties in shaping engineering knowledge and its embodiment in routines. Those parties included the American Society of Civil Engineers (ASCE) and the engineering trade press. We also explore the legacies of James Eads and his St. Louis Bridge in shaping the organizational routines used to build p. 174 long-span bridges later in the nineteenth century. The chapter ↳ concludes by considering how these historical actors contribute to our understanding of some larger questions: the roles and capacities of firms, the drivers of innovation in steel bridges, and the varied motivations behind new routines to organize project-based engineering.

Long-Span Bridges and the American Railway Network

In April 1865, America's jousting railway companies confronted three formidable natural boundaries to further expansion: the Ohio, Mississippi, and Missouri rivers (see Figure 6.1). Compared to eastern rivers like the Susquehanna, these big waterways presented huge challenges to civil engineers. At that time, no railroads crossed the Missouri River, even though work had begun on the Union Pacific's cross-country line from Omaha, on the west bank of the river. Two lines did cross the Mississippi River in April 1865, and their bridges exemplified the embryonic stage of this new engineering and business challenge. Built by an independent bridge-financing/operating company, the 1856 Rock Island Bridge used six iron-reinforced wooden Howe trusses to cross the upper Mississippi from Illinois into Iowa.[5] A pivoting draw span, also wooden, opened to allow steamboats to pass this low crossing. This venture had a charter from Illinois, but none from Iowa or from the federal government, which made it an illegal structure.[6]

Figure 6.1.

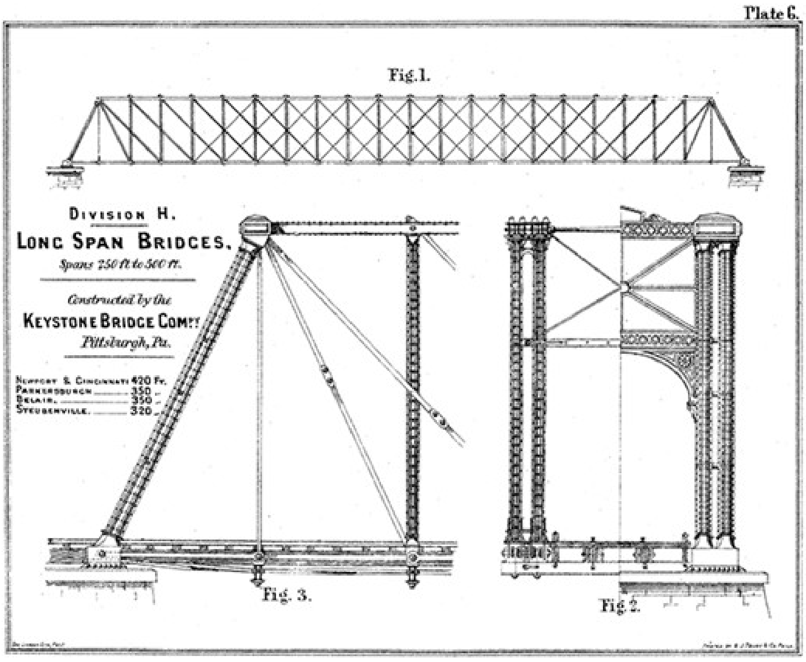
This map shows the twenty-six long-span railway bridges built on the Ohio, Mississippi, and Missouri rivers between 1856 and 1879. Public domain image created by Christopher Gist, Spatial Data Center, University of Virginia.

The Clinton Bridge, completed in January 1865, and located thirty-five miles upstream from Rock Island, also used composite trusses of wood and iron for its fixed spans. Its innovative feature was a 300-foot-long truss, made entirely in iron, that turned on a central pivot to allow the passage of river traffic. Unlike the business model that soon became common, a railroad originated and owned the Clinton crossing. It was designed and built by a specialist firm, the Albany Bridge Company. This time the venture did have charters from both states, but it lacked any federal authorization until Congress later declared it a post road.

The only rail crossing of the Ohio River in 1865, the Steubenville Bridge (from Ohio to West Virginia) became a legal, technological, and organizational model—repeatedly emulated over the next fifteen years across the Midwest. Congress debated this interstate project in July 1862 at the behest ↳

of the Pennsylvania Railroad (PRR). Despite the wartime need for better rail links, a Pennsylvania senator, Edgar Cowan, nearly killed the project intentionally. The original draft of the authorizing statute for this interstate structure called for a 200-foot span over the main river channel. Steamboat interests pushed for a 270-foot span, exceeding by 20 feet the longest American rail bridge then in service. Cowan wanted to wreck the project, believing the PRR threatened democratic institutions; and he wrote a nearly insurmountable obstacle into the enabling statute.[7] The main channel segment at Steubenville had to span 300 feet.[8] To achieve this unprecedented project, President J. Edgar Thomson of the PRR set up a bridge-financing/operating company, and in 1862 authorized and helped to capitalize a new independent bridge-building company. This firm, Piper and Shiffler, largely stripped the PRR of its in-house design/build capacities for bridges.[9] Thomson thereafter awarded it many of his railroad's contracts for new bridges. In 1864, the Steubenville Bridge opened, carrying mainline traffic to and from the PRR (Figure 6.2). The innovative iron-truss bridge was designed by Jacob Linville, chief engineer of Piper and Shiffler, and erected by that firm (which a year later incorporated as the closely held Keystone Bridge Company). At 320-foot long, Linville's main channel span exceeded the congressional mandate, establishing Keystone as a major player in the new industry of iron bridges.

Figure 6.2.



Keystone Bridge Company published these partial views of the Steubenville Bridge in its 1874 catalogue. It became the model for other fixed high bridges on the Ohio River. Public domain image from Keystone Bridge Company, *Descriptive Catalogue of Wrought Iron Bridges* (Philadelphia, PA: Allen, Lane, and Scott, 1874), available at the online resource, Making of America, at <http://quod.lib.umich.edu/m/moa/ajr3428.0001.001/57?view=image&size=400>.

Steubenville became the model for crossings on the demanding western rivers. Their environmental challenges were unprecedented: strong currents—especially in spring floods—with shifting banks, sandbars, and riverbeds in every season, and thrusting ice floes in winter. These natural conditions could threaten the piers supporting the bridges and the foundations beneath the piers and abutments. Preserving open navigation for steamboats presented more challenges: a need for wide clearances between piers with either pivoting spans (for low bridges) or high superstructures (for fixed bridges) so that vessels could pass
p. 177 unimpeded. Moreover, builders generally had to put up ↳ these bridges at locations far removed from talents embodied in cities, factories, and skilled workforces.

Amid the speculative fever for railroads, such obstacles simply became ongoing elements in the bridge builders' business. Between 1865 and 1879, five rail bridges opened over the Ohio, while ten more crossed the upper Mississippi (at various points in its 560-mile length between St. Louis and Minneapolis), and eight newly spanned the Missouri (see Figure 6.1). Of these twenty-three bridges, all but one began with congressional authorizations. Nearly all were ordered by independent bridge-financing/operating companies that laid down basic specifications within the authorizing statutes' requirements. Most were designed and erected by specialized bridge builders, firms like American Bridge (Chicago), Baltimore Bridge,
p. 178 Detroit Bridge and Iron, and Keystone Bridge (Pittsburgh). Early in this period, their designers ↳ and contractors struggled to fully understand the challenges inherent in their work, especially on the Missouri River, which the engineers saw as a wild and capricious adversary.[10] Responding to pressure from boatmen, legislators also imposed difficult challenges in their authorizing statutes, for example requiring fixed high spans (50 feet of vertical clearance) for three Missouri River crossings and for the St. Louis Bridge over the Mississippi. Congress also pressed for record span lengths: its 1866 authorization for a bridge at St. Louis set as the *minima* two spans with 350-foot clear openings or a single span of 500 feet, all exceeding the record set at Steubenville just two years earlier. In all, legislators, designers, and builders pushed repeatedly to advance the state of the art in bridge design and construction. These long bridges are the main focus here, just as they were in the trade press of the era.

At the same time, the big bridge builders and countless smaller contract shops also turned out innumerable shorter spans for railroads, cities, and counties across the country.[11] In a very real sense, the firms in this highly competitive industry transformed these prosaic, everyday bridges into a commodity, sold from catalogues or by competitive bidding.[12] And all too often those prosaic bridges fell down, causing great public outcry, frequent lawsuits, and, for engineers, some real soul searching. Outright failures were rare among the long bridges, but their unique design demands also motivated new routines among the firms
p. 179 collaborating to build them. ↳

Specifications and Routines for the Early Long-Span Bridges

The first generation of American civil and railway engineers had many sources and methods to guide their designs and specifications for railway bridges, everything from English and French treatises on the resistance of materials, to new American handbooks by Squire Whipple and Herman Haupt, to standard rules of thumb for dimensions and cross-sections of parts, to outright copies of bridges that had stood the tests of usage and time. As we know from technological historian Eda Kranakis, American builders relied primarily upon an empirical, practice-based design process that originated in construction and worked out its principles inductively.[13]

By the 1860s, however, this empirical approach was on the way out. The process began with a change in bridge-building materials. During that decade, wood increasingly gave way to iron for a number of reasons, especially in longer crossings for railroads. Durability was one obvious advantage. Iron also offered superior strength, allowing longer spans that carried heavier loads. An 1867 report by Grenville Dodge to his boss on the Union Pacific, Thomas Durant, acknowledged that wood was a feasible and cheap option for that line's proposed bridge over the Missouri River at Omaha. But Dodge pushed for iron, arguing that "in the end it will be better policy, and more economical to use it. So important a structure should take advantage of all improvements that genius and experience have added."[14] Dodge here was touting the genius of his own maturing profession of civil engineering. With the switch to iron, it became both possible and cost-effective to proportion individual parts in a truss bridge to bear their assigned loads—impelling engineers to now compute those loads, instead of relying upon the older rules of thumb that sufficed for wooden bridges.[15] Patented truss designs hawked by specialist firms also accelerated the move into iron.[16] The switchover p. 180 happened incrementally. ↳ Since the 1840s, many builders had used iron rods to carry tension loads, with wooden beams taking the compression forces.[17] Some of the empiricist builders of wooden spans then patented composite (wood and iron) bridges, and licensed their designs more or less broadly. For example, a Massachusetts farmer, William Howe, patented his composite Howe truss in 1840 with an eye to railroads' bridging needs (the first rail crossing of the Mississippi, the 1856 Rock Island Bridge, was a composite wood and iron Howe truss).[18] Within the decade, Howe's brother-in-law had opened a Chicago bridge-building firm, Stone and Boomer, which became the Boomer Bridge Works in 1856 and the American Bridge Company (incorporated) in 1870. By then, the firm was turning out long all-metal (iron) truss bridges for Midwestern river crossings, but as a contract shop American made whatever the customer wanted. For example, into the 1870s, the company made standard wooden-truss bridges for the Wisconsin Central Railroad.[19] On the other hand, by 1872 the demand for iron railroad bridges had grown to the point that Phoenix Bridge chose to specialize in that field, building no highway or wood bridges at all.[20]

Until 1860, railroads typically designed their own spans, or they contracted with local empirical builders; thereafter most turned to the new specialists.[21] In part this reflected the division of labor in an expanding market that Adam Smith had described. Beyond simple economies of scale, the contract or catalogue shops also developed specialized technical knowledge and capacities in design and production of composite and all-iron bridges. The new market also reflected the railroads' desires to save time (by getting bridges up quickly) and to push hard for competitive pricing—to save capital.[22] By the late 1860s, railroads, counties, or towns typically advertised for bids on these common bridges. This situation encouraged three strategies: p. 181 major makers ↳ tried to stem the price competition by hawking patented truss designs to distinguish their offerings. Most makers hid their own calculations of safe loads and working strains, as that intellectual property offered competitive advantage. In the markets driven by competitive bidding, some makers felt pressured to cut metal from their products, lowering costs and often strength as well.

These practices were readily denounced after bridge failures became a growing concern among professional engineers and the public across the 1870s. Those collapses had complicated roots in addition to the failure of competitive markets to reward quality products. Four generalizations seem warranted: common roadway bridges failed more often than did railway crossings, largely because less engineering skill went into these spans. The failure rate for railroad bridges, however, likely grew during the 1870s as aging wooden spans fell under increasing locomotive weights and train loads. The new long-span rail bridges were quite safe, as increasingly detailed engineering calculation went into their design. But public outcry for safer bridges of all types grew inexorably, fueled in part by some notorious failures. American engineers saw threats and opportunities in the public debate over bridge failures.[23] Both perception and reality combined to change the profession, its heuristics, and routines.

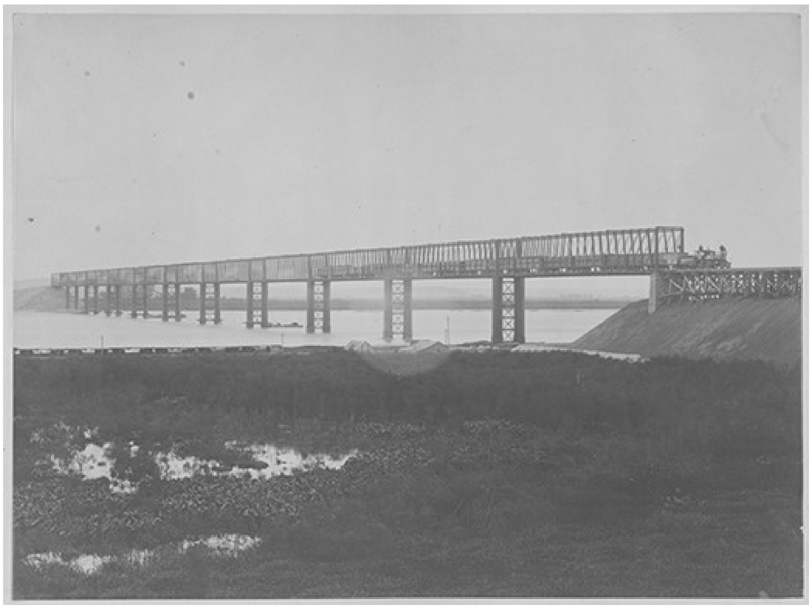
Until the early 1870s, railroad companies set pretty minimal specifications in ordering new metal bridges from the contract shops, another reason for the safety challenge. Commonly an invitation to tender (a "request for proposals" in modern terminology) gave only two specifications: carrying capacity and factor of safety. The first was a specification that the finished bridge be able to carry a given load, rendered in pounds per lineal foot of bridge. Typical specifications to about 1870 called for a live loading of 2,000 to p. 182 2,500 pounds per foot.[24] The desired factor of safety, typically 1 to 5, amounted to a ↳ railroad's statement to the contract shop that its design should not fail unless loaded five times beyond the design-carrying capacity.[25] The loading capacity was based on nothing more than the weight of the heaviest engines then in service, while the safety factor amounted to little more than a target—or a prayer.

Starting with these skeletal requirements, the contract shops worked up designs in their favored truss styles. Regardless of the style, the designer followed a common action pattern in this era. He started with four basic elements: the specified carrying capacity (mandated by the railroad), basic values for the tensile and compressive strength of iron (given in tables developed and published by Scots ironmasters, William Fairbairn and David Kirkaldy), experience derived from earlier work, and trigonometry. Wielding those guides, the designer sketched out dimensions for all the structural members in the truss (top and bottom chords, struts and ties, floor and wind braces, and so on). Excessive material in any member added costs and counterproductive dead weight which grew the overall load that the structure had to bear. So the designer was always calculating the weight (per lineal foot of bridge) of every element—truss, floors, sidewalks, railings. Yet he could not shave too closely, because far too many matters lay beyond his reckoning. Furthermore, the factor of safety guided him to proportion the main structural members to provide a measure of extra strength. Effectively the safety factor was a pragmatic and rudimentary response to a host of known unknowns: the engineer's incomplete and inadequate computational modeling of forces, the uneven qualities in materials and construction, inadequate maintenance of bridges in service, and likely growth in train loads over time.

Once he had optimal plans for the components, the designer created tables of the loads and strains using basic Newtonian mechanics and trigonometry. Whether in tables or graphic form, those data provided the core assurance of adequate strength in the design.[26] This approach to design sidestepped some tricky issues. Most notably, bridges bore simultaneous stresses from dead loads (chiefly the superstructure itself), moving trains, the heavy and unbalanced forces imparted by locomotives, variable winds, and temperature variations. Dealing accurately with all those additional and varied elements required the use of calculus, a technique beyond the capacity or interest of most American engineers until the 1890s when collegiate training became widespread. Even without calculus, the computational burdens were high. So designers
 used a convenient shortcut. Once they settled on the requirements of a single truss, ↳ they simply repeated that form whenever possible in multiple spans to achieve the desired overall length of the bridge. In all, these practical design methods proved effective. They also encouraged designers to prefer standard truss forms, to advance load capacities and span lengths incrementally, while discouraging radical innovations such as the steel arched spans that James Eads would propose for St. Louis.

With design drawings in hand, the contract shops then ordered iron from their own trusted suppliers—firms like Phoenix, Cambria, or the Union Iron Works. Those firms turned out standard structural shapes, including I-beams, channel sections, and bar stock in wrought (or rolled) iron. Some firms also sold patented structural specialties, for example load-bearing "Phoenix columns" became a worldwide standard. Using these standard elements, a bridge maker then fabricated the requisite parts in its shop. The big contract shops had extensive investments in powered machinery: punching machines that created a dozen holes at once, steam-powered plate shears to cut iron parts, and hydraulic riveters that set rivets better and faster than hand riveting. These fabrication methods meshed well with the dominant design paradigm in iron truss bridges, to use scores of identical parts in each truss while exactly repeating the trusses across the full width of river to be bridged. The central rationale for the contract shops lay in nested routines that linked iron bridge design to the tooling capacities and workforce skills on the factory floor.[27] At the big shops, complete trusses were temporarily assembled in the factory yard, using wrought iron pins to connect the beams, struts, ties, floor structures, and wind braces. These "pin-connected bridges" were uniquely American. Trial assembly in the shop ensured that erecting out in the field would proceed swiftly. The bridge was then knocked down, its components shipped to the railroad's site, and erected at that location, often using locally contracted labor supervised by experienced foremen.[28] The system worked equally well for bridges of just one span or many, such as the eleven-span Omaha Bridge that American completed in 1872 to Grenville Dodge's specifications (Figure 6.3). Phoenix Bridge claimed in 1873 that its crews typically assembled a 160-foot railway truss bridge (single span) on site in just 8.5 hours.[29]

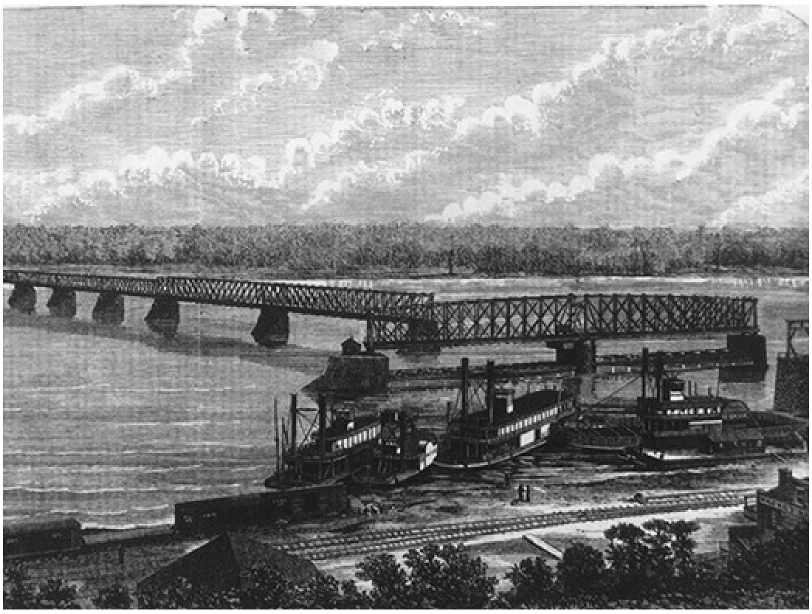
Figure 6.3.



American Bridge Company completed the eleven-span Omaha (to Council Bluffs) Bridge for the Union Pacific in 1872. Congress required fixed high spans at this location, as it did for St. Louis. Public domain image from "Council Bluffs and Nebraska Ferry Company and Union Pacific Transfer Album," image 13, in the collections of the Omaha Public Library. Available at <http://digital.omahapubliclibrary.org/earlyomaha/ferryco/fco_13.html>.

 Upon completion, a railroad typically undertook deflection tests of the finished bridge. This fancy term stands in for a pretty rudimentary event. At the Keokuk Bridge over the Mississippi (superstructure by Keystone Bridge) deflection testing entailed running five locomotives, coupled together, across the bridge's eleven spans (Figure 6.4). A surveyor standing safely on firm ground, sighted through a transit to a rodman on the bridge as the locomotives passed over each span. Looking through his instrument, the transit man could literally see the bowing effect of the load—which he recorded in inches (up to 1 and 3/4 inches at Keokuk). After completing the deflection testing, the surveyor also recorded the amount of "permanent set" in the bridge, the amount of bowing that remained after the load came off (1/4 inch at Keokuk).[30] And that was it; the bridge entered regular service.

Figure 6.4.



Keystone Bridge Company completed the twelve-span Keokuk and Hamilton Bridge over the Mississippi in 1871. Unlike the high fixed bridges at Omaha and St. Louis, Congress allowed low bridges on the upper Mississippi with a pivoting drawspan to allow vessels to pass (here the drawspan was 380 feet long). The operating company that owned this structure was never profitable. Image from *Scientific American* 30 (May 23, 1874): p. 323. Available at <http://search.proquest.com/docview/126730148/74ECD8114E4843B7PQ/23?accountid=14678> (accessed June 28, 2015).

p. 185 Leading bridge engineers of the day pushed hard to develop more rigorous specifications and routines for testing materials and finished bridges—routines based in mathematics, physical testing of materials, and new standards for elasticity (or resilience) in iron parts. There was certainly room for improvement.[31] Before turning to those innovations, we need to explore the informal methods that also guided these big bridge projects at the onset of this period. Here we see a web of safeguards, all reaching across firm boundaries. Few were embodied in contracts or specifications, yet all were vitally important to the success of these special projects and increasingly essential to the evolving practice of the industry. In the p. 186 terminology set forth in Cohen et al., ↳ these informal methods are not "routines" at all. Rather they appear to be heuristics, rules of thumb, and strategies that served in place of routines.[32]

First consider experience and branding. Typically we think of branding as a post-Civil War development in consumer goods, but many makers of raw and finished iron products projected clear brand identities by 1860. The best British brands of rolled and wrought iron products, for example Lowmoor, commanded a premium price around the world. American ironmakers also cultivated brand recognition. The qualities of raw iron arose directly from the ores and fuels used to make it; in turn iron chemistries varied widely across different regions. So iron from the Catawba (Virginia) furnace commanded three times the price of pig iron from Glendon (Pennsylvania).[33] Wise bridge builders established ongoing relations to iron suppliers known for quality.[34] Phoenix Bridge used only Phoenix Iron; Keystone Bridge turned whenever possible to the Union Iron Mills.

Personal and professional ties also safeguarded quality and performance in projects that crossed firm boundaries. The major bridge fabricating firms of 1870 all had chief designers, men highly regarded in the profession such as Simeon Post at American Bridge, Shaler Smith and Benjamin Latrobe at Baltimore Bridge, and Jacob Linville at Keystone. Their firms all competed for contracts for the big western crossings. Even so, the engineers shared advice and experience quite freely.[35] Typically the bridge-financing/operating companies behind the big western crossings had their own chief engineers. For the Quincy (Illinois) bridge over the Mississippi, Thomas Curtis Clarke filled that role for the financing company even as engineers at Detroit Bridge and Iron designed the superstructure.[36] The Civil War superintendent of the U.S. Military Railroads, Anda Anderson, was engineering chief for a proposed St. Louis crossing (never built), with a design by Simeon Post, to be supplied by American Bridge.[37] On the really big jobs like the St. Louis crossing, the primary design engineer (employed by the financing/operating company) typically convened a p. 187 professional panel to review his design before it became final.[38] ↳ These ongoing professional interactions became another informal action pattern to assure a high-quality result.

Published accounts that offered knowledge gleaned from experience provided a third safeguard for these early bridge projects. In the typology of action patterns offered by Cohen et al., these articles and books demonstrate qualities of "strategies" to approach design and construction problems and the formulation of "paradigms" to solve them.[39] Quite commonly, the engineers who built the long bridges immediately delineated their challenges and solutions in print. Thomas Clarke published a full volume on his Quincy (Illinois) crossing of the Mississippi, and Octave Chanute wrote a highly descriptive account of the design and construction of his Kansas City bridge over the Missouri.[40] Journals like *Engineering* (London), *Engineering News, Railroad Gazette*, and *Scientific American* published reams of illustrated material on all the big projects, during or after their construction, thanks to extensive cooperation of designers and builders. While some puffery was at work, a collaborative spirit also animated these descriptions, aiming to advance the profession of civil engineering and the state of the art in long-span bridging. The editor of the *Railroad Gazette* warmly introduced Chanute's book, saying "This detailed report…gives a history of obstacles met and overcome which can hardly fail to interest and to instruct all who have to do with such structures."[41]

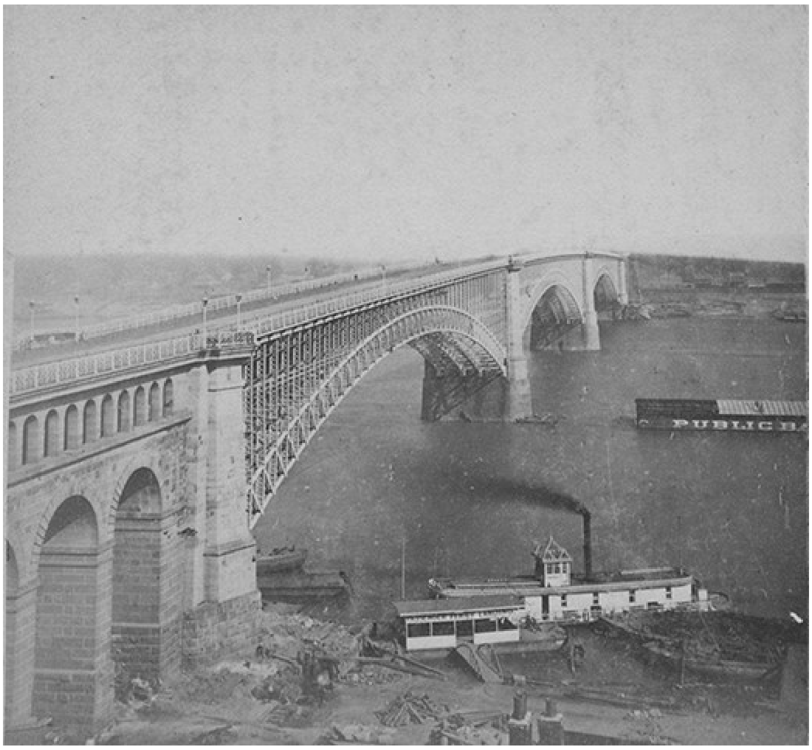
In all, these action patterns, heuristics, strategies, and paradigms worked well in creating the designs, practices, and collaborations behind the long bridges. By December 1871, seven new iron bridges had opened on the Mississippi, two on the Missouri, and one on the Ohio. Many broke records for the longest channel spans, those laurels passing quickly from one bridge to another. Ironically enough, shorter bridges were more problematic, largely because they appeared more prosaic, needing (and getting) less engineering oversight and specification.[42] Furthermore, short spans needed stronger specifications than did longer bridges whose structures were designed to distribute broadly the live load of a passing train, a p. 188 counterintuitive fact then and now.[43] ↳ Thoughtful engineers passionately advocated for new formal and rigorous routines to guide bridge design and construction for all sizes and types. For example, Alfred Boller wrote a series of "Papers on Bridge Construction," published in the *Railroad Gazette* in 1872 detailing a number of issues that lay outside of contemporary specifications and routines.[44] Boller complained that many bridge designers left it to contract bridge shops or to ironmasters themselves to specify grades or quality of iron, perceiving that field as a "variable and deceptive" mystery. He also believed that designers had a fallacious understanding of iron's strength, failing to appreciate that its ultimate strength (measured by the load it bore just before breaking) mattered less than its elasticity or resilience, its capacity to bear a heavy and variable load repeatedly without permanent deformation or fracture. A third Boller indictment: designers and bridge builders were only slowly distinguishing between cast and wrought iron, yet the two materials had very different qualities. He offered a rueful verdict in favor of wrought or rolled iron as it "shows its defects" more clearly than did iron castings. Finally, Boller criticized railway civil engineers for failing to realize (and to specify for) the variability of the loads that were actually borne on their bridges. The passage of trains imposed sudden shocks and temporary loads, while bridges near terminals handled much more frequent traffic than did remote locations. In this indictment, he recognized what we today call metal fatigue.

A Fresh Start in the St. Louis Bridge

At the time Boller's papers appeared (1872), a bridge project in St. Louis that had begun five years earlier was already developing new routines, specifications, and heuristics—many reflecting Boller's concerns. James Eads was an improbable engineering innovator. Born poor in 1820 and possessing a rudimentary education, Eads first struck success on the bottom of the Mississippi, salvaging the cargos of sunken steamboats, the major commercial hauler of the antebellum Midwest. Mixing originality and nerve, Eads used a diving bell, salvage gear, and vessels of his own design to find and recover wealth from the riverbed. By the 1850s he had become a pillar of the St. Louis business community. In 1867, his focus shifted to railway investments, focused on the new North Missouri Railroad that sought to tap that region and p. 189 southern ↳ Iowa to the benefit of St. Louis. Getting into the railroad business as an investor quickly led Eads to the bridge business. To realize its potential, the North Missouri would need a connection to the maturing rail network of the east. By March 1867, Eads resolved to connect east and west with a new rail and highway bridge over the Mississippi. The river was not especially wide at St. Louis—at 1,500 to 2,000 feet—but the city is just south of the confluence of the Missouri and Mississippi rivers, resulting in swift currents and severe icing in winter.

James Eads possessed equal measures of engineering creativity, organizational skill, and headstrong resolve. In promoting his own St. Louis bridge (Figure 6.5), Eads directly competed with another local bridge-financing/operating company, one with strong ties to American Bridge, the dominant contract shop for truss bridges in the West. Eads's group pushed past that rival, while offering a paradigm for long-span p. 190 rail bridges that broke entirely from ↳ the standard truss forms.[45] Eads unveiled his plans in the summer of 1867. Although the design evolved in details, its larger concepts dated to that first version and exist to this day. The bridge has three shallow arched spans, each roughly 500 feet in length. The main structural members of each span combined two steel tubes braced together (one above the other) to form a beam or chord, a combination far stronger than its component parts. Four of these chords (that is, eight tubes in all) in each span carried a dual-track railway deck and an upper deck for common roadway traffic.

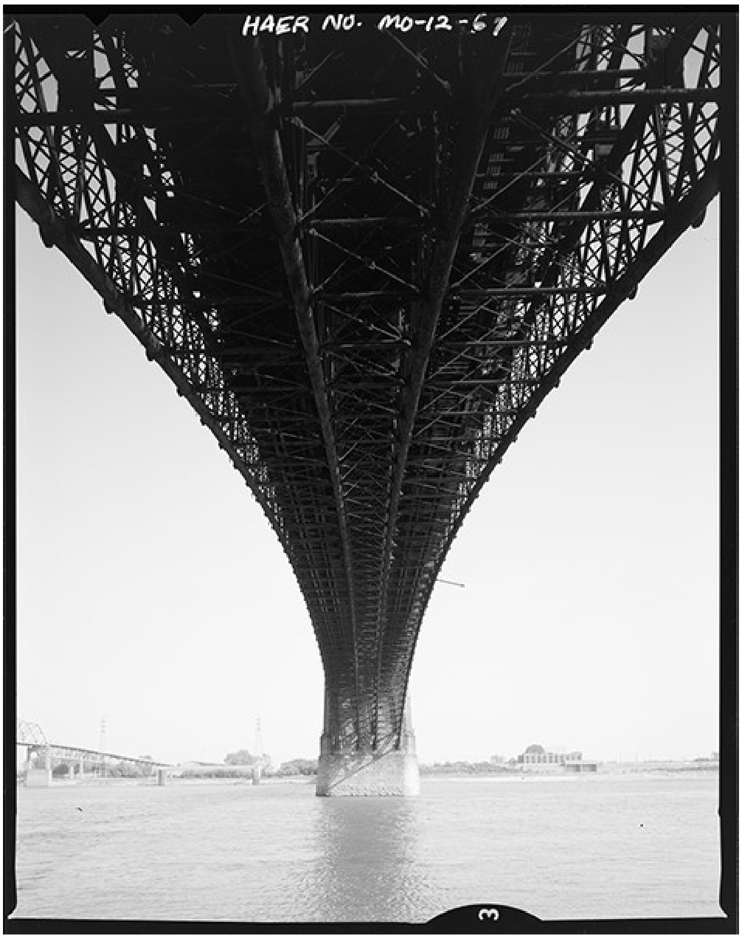
Figure 6.5.



The St. Louis Bridge in the 1880s, looking at the Missouri shore in the distance. Public domain image from the author's collection.

The weight of the arches, decks, trains, and traffic passed into two massive piers in the river (Figure 6.6). The two river piers and the two shore abutments, made of sandstone and granite, went all the way down to bedrock far below the turbulent currents and the sandy river bottom.

Figure 6.6.



Here we see the main structural members supporting the St. Louis Bridge. Each span had four “ribs” in Eads’ terminology, each composed of two steel chords, one above the other, extensively braced by wrought iron, making a total of eight steel beams. Public domain image by Jet Lowe, Historic American Engineering Record, Library of Congress. Image number HAER MO,96-SALU,77-67. Available at <http://www.loc.gov/pictures/collection/hh/item/mo0361.photos.191689p/resource/> (accessed June 27, 2015).

Despite his lack of engineering training (or arguably because of it), Eads made these basic design choices by himself at the very onset of the project, choices that broke entirely with the common paradigms for rail bridges in American engineering practice of the day. He did find some scattered inspirations in the U.S., including Philadelphia’s Chestnut Street Bridge, a cast-iron arch bridge completed in 1866.[46] He also credited an 1864 railway bridge in Koblenz, Germany, composed of three shallow wrought iron arches.[47] In his first report as chief engineer, Eads admitted he had little interest in precedents. In this design, he sought to build an effective rail connection and—in the roadway above—to create a grand public space, a processional entrance into St. Louis. By avoiding the commonplace truss form, his design offered unobstructed views of the river and the city.

Aware of Eads’ inexperience in bridges, another investor in this venture, Thomas A. Scott of the Pennsylvania Railroad, arranged for St. Louis Bridge to hire Jacob Linville as consulting engineer in May of 1867. Scott likely foresaw a chain of benefits from this simple act. Lead designer at Keystone Bridge, Linville had completed the paradigm-setting Steubenville bridge three years earlier. Once installed in St. Louis Bridge, Linville would no doubt push aside Eads’ unusual design (if not Eads himself), substitute his own plans, throw the work to Keystone, and thus give Scott a backdoor benefit as he held a hidden equity stake in Keystone. Eads did submit his design for Linville’s review, and he got a stinging critique. Linville wrote “I cannot consent to imperil my reputation by appearing to encourage or approve of its adoption. I deem it

p. 191 entirely unsafe and impracticable as well as faulty in the qualities of durability ↳ so essential in a structure of so great magnitude."[48] Scott's scheming did not quite work out, since the board of directors at St. Louis Bridge responded to this blast by abolishing the post of consulting engineer. Linville, not Eads, was out of a job.

p. 192 Nonetheless, Linville had legitimate concerns. Thanks to Henry Bessemer, steel in 1867 was just transitioning from an exotic material, known since antiquity and used for swords and special tools. But steel in the reliable quality and quantity that Eads would need simply did not exist anywhere in the world. The material was unknown in bridges specifically and in structural engineering generally.

Furthermore, Eads' arched design had far more complicated internal forces than any truss bridge. He proposed to gain rigidity in his steel tubes by bracing them together with wrought iron members. The braces would themselves impose unknown strains on the steel chords (see Figure 6.7). Linville perceived that temperature variations would cause further strains across Eads' superstructure as the steel lengthened on hot days, causing the arches to rise, while in winter they would flatten somewhat. In all, the arches raised a number of problems unknown in truss bridges. One was especially troublesome. In the multi-span truss designs used for all other rail crossings of the western rivers (such as those shown in Figures 6.3 and 6.4), each span was structurally independent. In other words, the deadweight of that span and the weight of any load (train) on it passed directly downward onto the pier or abutment at each span's end. Instead of that simple downward force, in Eads' design each of the three spans exerted thrust or axial loads (along the length of the bridge) into the piers or abutments on which it landed. More challenging still, as temperature variations altered the form of each arch, the forces acting in the steel tubes would change. And when a train passed over the bridge, that live loading further altered the forces (tension and compression) acting on each chord. Concerned about these complicated and variable forces, Eads proposed to connect each arch to its neighbor, using massive steel bolts, 30-feet long, that would pass through the stone piers.

Figure 6.7.

This image shows how the two chords or steel beams in each rib land on the piers, passing dead and live loadings into the stonework. The bracing between the chords induced other loadings, and the relative share of those loads borne by each part of the superstructure shifted with temperature variations. To understand and chart all these stresses, the design team at St. Louis Bridge used calculus. The designers also took a "belt-and-suspenders" approach. Look carefully at the fabricated "skewbacks" where the round tubes land on the piers, and note the hex nuts there. They fasten massive bolts that pass right through the piers, connecting each arched rib to its neighbor in the adjacent span. That rigid connection made the structure "indeterminate," incapable of being modeled in trigonometry. Public domain image by Jet Lowe, Historic American Engineering Record, Library of Congress. Image number HAER MO,96-SALU,77-68. Available at <http://www.loc.gov/pictures/collection/hh/item/mo0361.photos.191690p/resource/> (accessed June 27, 2015).

That design choice highlighted the central problem motivating Linville's critique. By bracing the steel chords together, then by connecting the arches rigidly to the piers, Eads had created a design whose internal forces were too complex and intermixed to model using trigonometry and algebra. Engineers would later describe such designs as "indeterminate" structures, testament to the challenges in modeling them. By contrast, Linville's preferred design was a well-proven truss, whose pin connections avoided, isolated, or dissipated most of the forces that Eads' design combined and amplified.[49] Still, Eads refused to alter his essential design choices.[50] Instead he resolved to address Linville's concerns by innovating new routines in bridge design. ↳ p. 193

p. 194 Even before this clash, Eads had begun to assemble a professional design team for St. Louis Bridge. An émigré from Bavaria, Henry Flad signed up in March 1867. He brought civil engineering training from the University of Munich, experience designing docks on the Rhine, as well as wartime work on the U.S. Military railroads. In August 1867, another assistant engineer joined the payroll, Charles Pfeifer. Only twenty-four, Pfeifer was another well-born émigré from Bavaria. His unique talent lay in higher mathematics, "the calculus," as many still called it. Before emigrating, Pfeifer had served on the design staff for the Koblenz crossing that Eads saw as an exemplar. Using his advanced mathematical training, Pfeifer's work in St. Louis would center on calculating the stresses that the bridge had to bear.[51] Beyond the dead load of the bridge itself the engineers had to plan for the live loads of passing railway trains, the transient loading imposed by winds, and the challenges of temperature-induced strains. Only Pfeifer's calculus could integrate those variables. His calculations delineated the forces which the structure would have to bear, in turn guiding the sizing and configuration of its steel and iron components, and the strength needed in those parts. Even with calculus, the team needed eighteen months for calculations and redesign to settle on the final sizing of the steel tubes (18 inches in diameter) and their spacing, the two tubes in each chord finally placed 12 feet apart, one above the other.[52] Given the importance of all this analysis, Eads also took the precautionary step of hiring a professional mathematician, William Chauvenet, then chancellor of Washington University, to verify the calculations.

In these two steps: creating a design team and using calculus as a design tool, James Eads gave to St. Louis Bridge a new ability to analyze and model his bridge as a whole and in its component parts. In doing this, Eads created a new power, unprecedented in the developing American bridge industry, to dictate specifications to whatever firm St. Louis Bridge selected to make and erect the superstructure. Eventually, these methods became accepted routines in the industry. With these steps, Eads shifted the essential power over design from the contract shops to the bridge-financing/operating companies. In relying on a trained engineering team using calculus, St. Louis Bridge was ahead of its time, for most American-born engineers simply did not know how to wield this analytic tool. An advocate of calculus, writing in 1871, described the
 consequences that flowed from American engineers' lack of higher ↳ mathematics. Unable to undertake "the long calculations indulged in by foreign Engineers," the Americans stuck with their "straight truss bridges... [even] where arches might have been more economically employed."[53]

Having made these design choices, the team at St. Louis Bridge also created new routines for bridge construction, seeking to ensure that its contractors obeyed its directions. Again, Eads had to act largely because his design choices were utterly novel, particularly his choice of steel tubes as the main structural members, rather than the riveted wrought iron beams, struts, and ties commonly used in trusses. The first American Bessemer works opened in Troy, New York in May 1867. It made steel rails, a simple product that would soon replace rolled iron rails across the country. A month later, Eads placed the future of his bridge—and his own reputation—in steel. It was a breathtaking leap of faith. His bridge would be the first structure of any kind, anywhere in the world, to use steel for its main load-bearing members.

His design choice for long and shallow arches had pushed Eads to steel. Contemporary English tests by William Fairbairn had shown that the best British steels possessed twice the breaking strength of quality wrought iron. Steel was especially strong in compression, the primary loading in an arch.[54] Better yet, steel parts offered higher strength at lower weight than wrought iron components. Eads proposed to build a record span for St. Louis, fully 200 feet longer than Linville's Steubenville crossing. In these big bridges, strength without excess weight became the core challenge. But how could St. Louis Bridge be sure it was getting the strength it needed in this novel material?

To ensure that suppliers knew and fulfilled his standards, Eads established three specifications for the steel in the arches. A mandate for "elastic limit" measured how much strain any component could bear before it became permanently deformed (such deformation was called permanent set). Eads required his steel to bear an elastic limit of 60,000 pounds per square inch under compression and 40,000 pounds under tension. He also required an "ultimate tensile strength" of 100,000 pounds, tensile strength being the load at which the steel simply broke apart. Finally, he stipulated the "modulus of elasticity," a "ratio between stress and deformation and a far more revealing figure" than elastic limit or tensile strength alone.[55]

The Eads team did not originate the concept of an elastic modulus; it appears in Herman Haupt's 1851 guide to the theory and practice of bridge construction.[56] But until Eads few designers or builders of metal bridges p. 196 paid much attention to the core issue embodied in the modulus. They focused on ↳ the ultimate strength of iron, its breaking strain, little realizing that structural members needed resilience under loads, also described as elasticity.[57] This ratio of strength to deformation became a common specification, a design routine, after the St. Louis Bridge.

It was one thing to mandate strengths, another entirely to verify them. St. Louis Bridge built its own piers and abutments, and entirely designed its superstructure. Then it contracted with Keystone Bridge to make and erect that massive creation. Keystone in turn subcontracted for steel with the William Butcher Steel Works of Philadelphia (reorganized as Midvale Steel in 1872). Even before it had lined up a steel supplier, St. Louis Bridge designed and built its own materials testing machine, which it installed in its St. Louis office. The machine could exert upwards of 100 tons of force while its graduated scales showed how much a sample shrank (when compressed) or lengthened (in tension). Readings extended out to a hundred-thousandth of an inch (0.00001).[58] Under its contract, Butcher built a second testing machine in Philadelphia. The machine was busy; St. Louis Bridge required compression tests of every piece of steel destined for the chords that were the backbone of the bridge. St. Louis Bridge had its own inspector at Butcher to ensure that each steel part had its modulus of elasticity stamped into the metal.[59]

That Butcher struggled mightily to produce adequate steel for the St. Louis project is a well-known story in industrial history.[60] After its steel components repeatedly failed the testing regime, St. Louis Bridge arranged for Butcher to use a patented chrome-alloy steel instead of his own hit-or-miss formula for carbon steel. Eads also had to ease his own specifications simply to get the job done, substituting iron for steel in some key components. Subsequent accounts all focus on Butcher's struggles as conclusively demonstrating the need for chemical testing of steel, a capacity that Midvale developed after 1872. Chemical tests would eventually become a key routine within steel firms. But only physical tests, like those required by St. Louis Bridge, served to bring firms together on the clear terms required to get these bridges built to the mandated specifications. Chemistry was simply a means to achieving contracted requirements for strength and elasticity and born out, for all to see, in testing machines and written specifications for tensile strength and elasticity. At the time, Keystone complained bitterly about Eads' exacting standards, but it too p. 197 built its own testing machine. After Eads completed his bridge, largely to his ↳ own specifications, his St. Louis machine went to Jones and Laughlin, underpinning new routines at that Pittsburgh maker of structural ironwork.[61]

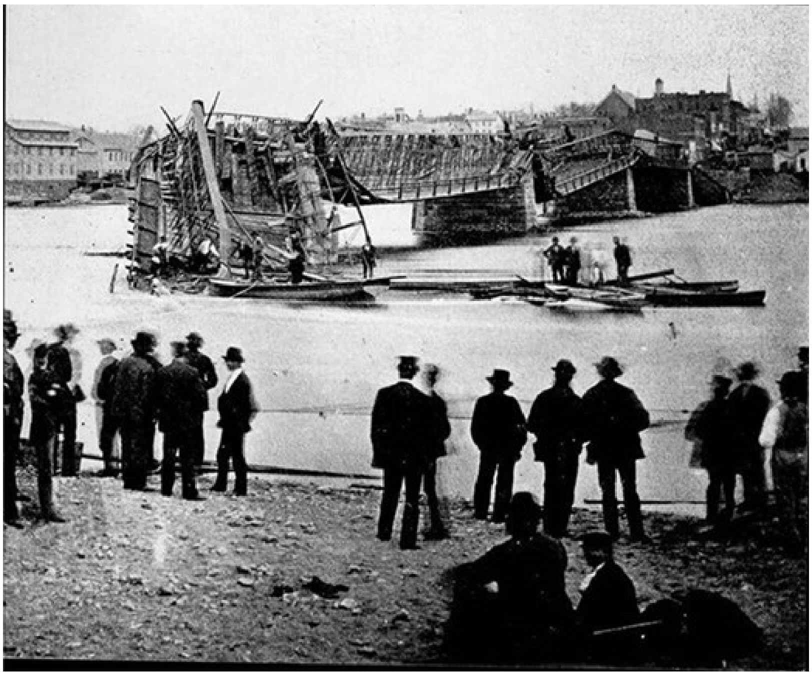
Beyond its specifications for strength and elasticity, St. Louis Bridge also laid down requirements for the production of its iron and steel parts: drilled holes instead of punched work, forgings instead of castings, and so on. Pleading for Keystone, Andrew Carnegie (a Keystone shareholder and its chief salesman) wrote that all this specification was unreasonable, instead "Captain Eads must only require the custom of the trade."[62] In the short term, St. Louis Bridge generally won these battles, although at extra cost. In their larger significance, we again see here a shift in how different parties came together to create these projects, a shift from trade customs (heuristics) to formal procedures. In its innovative design and contracting requirements, St. Louis Bridge caused equal measures of heartache for William Butcher and Keystone Bridge. Its unique design originated in Eads' fearless innovating and from the statutory requirements that the U.S. Congress mandated for any bridge at St. Louis. Quite directly if unwittingly, legislators changed the practice of engineering.

Failures and a Restart

The approaches developed by St. Louis Bridge might have proven one-offs, oddities without enduring effect. After all, James Eads' shallow arches never took hold as a design paradigm in American civil engineering, while structural steel remained unusual in long-span bridges until the 1890s. Every other rail bridge described in this chapter, twenty-five in all, were truss structures, not arches. But these new routines in the design and construction of long-span bridges did spread across the 1870s and 1880s. The first mechanism was simple enough. Engineers from the St. Louis team carried across the country the knowledge and routines first developed there. Beyond Pfeifer and Flad, Milnor Roberts and Theodore Cooper both worked on the St. Louis Bridge and then moved on to influential jobs in civil engineering. Roberts became chief engineer of the Northern Pacific Railroad, overseeing much of its construction from St. Paul, Minnesota to Portland, Oregon. Cooper was a design or consulting engineer for dozens of major bridges during the Gilded Age. As important in this context, in 1894 he created an influential design routine for railway bridges, standardizing the calculations and analysis used to ascertain the safe loading of such spans. Engineers still use Cooper's Loading System to design modern bridges.[63]

p. 198 The catalogue bridge industry might have resisted many of the new routines pioneered at St. Louis Bridge. After all, they shifted power away from the bridge builders, while also demanding new knowledge and sophisticated techniques from design engineers. But some catastrophic failures of iron bridges across the 1870s helped to ratify the new routines in practice. In 1873, a four-year-old iron road bridge collapsed into the Rock River (Illinois), killing forty-five (Figure 6.8).[64]

Figure 6.8.



Completed in 1869, the Truesdell Bridge was the first iron bridge across the Rock River, its five spans each 132 feet long. This road and pedestrian bridge was crowded with people on May 4, 1873, there to witness a Baptist preacher as he immersed converts in the Rock River. With almost no warning, the bridge collapsed under the unusual load, killing forty-five spectators. This 1873 photo was originally published in the Dixon (Illinois) *Telegraph*, and reprinted in Patrick Gorman, "Guest Column: Dixon Bridge Collapse Was City's 'Darkest Day,'" *Rockford Register Star*. Available at <http://www.rrstar.com/opinions/whatyouresaying/x919542180/Guest-Column-Dixon-s-Darkest-Day-revisited?photo=0> (accessed June 27, 2015).

p. 199 In response, the young ASCE appointed a committee to investigate the "most practicable means of averting bridge accidents."[65] Its distinguished members (including James Eads) offered a number of recommendations, but the seven members could not agree on much, issuing four reports. In December 1876, an iron rail bridge at Ashtabula, Ohio collapsed as the *Pacific Express* crossed. Eighty-nine people died, the worst rail accident of the century. The all-iron truss bridge was only eleven years old; furthermore its designer, Amasa Stone, had thirty years of experience in the design and construction of composite Howe bridges.[66] The coroner's jury, however, levied responsibility for the disaster against the railroad (the Lake Shore and Michigan Southern) rather than against Stone personally.[67] In the aftermath, civil liability judgments against the railroad exceeded $600,000.[68] That crushing burden caught the attention of railway presidents and chief engineers across the country.

To the engineering community, the Ashtabula failure highlighted the shortcomings of existing routines (especially deflection testing) and the need to replace design heuristics with sound specifications.[69] For their part, railroads responded to such disasters and liability judgments by improving their own routines in specifying bridge designs. For example, in October 1877, the Western Union Railway solicited bids for a new iron bridge for its main line over the Rock River (Illinois). Later published in the *Engineering News*, the specifications included mandates for the tensile strength and the elastic limit of all major components. Further details covered wind strains, the dynamic loads of moving locomotives, and an added allowance for the effect of a train's momentum. The carrier also required the successful bidder to submit strain sheets for each span, a graphic representation of the strains carried in every component of every span. Other specifications reached directly into the builder's shop, mandating drilled holes rather than punched,
p. 200 hydraulically forged rather than forge-welded eyebars, and so on. The successful bidder had ↳ to submit all working or shop drawings to the carrier for approval before the work began, and the railroad assigned its own inspector "who will examine and test the iron at the rolling mill…with full power of rejection."[70] A few months later, *Engineering News* published similarly detailed specifications by the New Haven, Derby and Ansonia Railroad to guide bidders for its proposed iron bridge over the Naugatuck River. Working for the Erie Railroad, Theodore Cooper drafted in 1878 the first set of fully comprehensive standards to guide the design and fabrication of all its new bridging needs. He claimed three benefits for the new heuristics and routines: they laid down general principles in design, proportioning, and fabrication—principles applicable to spans of any length and suited to evolving needs. With these frameworks, railroads could seek competitive bids for any bridge, driving down costs while advancing safety. And thanks to their comprehensive quality, the new heuristics and routines omitted entirely "that relic of ignorance, 'the factor of safety'"—in Cooper's arch phrasing. Cooper had served as a key assistant engineer in the St. Louis Bridge project. Laid down for the Erie, his standards "were adopted very widely" by carriers across the U.S.[71]

Cooper's Erie standards and those from the *Engineering News* both reflected and reinforced broader changes in the railroad and bridge-building industries.[72] And those changes had other roots beyond the Ashtabula tragedy, the coroner's jury verdict against that carrier, or the broader problem of bridge failures in the decade. A Chandlerian view would underscore growing professionalization in railway management across the 1870s, certainly another factor.[73] In all, these new routines show a thorough reordering of responsibilities, with power shifting—through formal engineering specifications—away from ironworks and bridge shops, toward the customer. At least this was true for the more sophisticated customers, such as the independent bridge-financing/operating companies and the larger railroads. In broad outline and in many specific details, the organizational model pioneered at St. Louis Bridge was reordering the industry by
p. 201 the late 1870s. ↳

Postscripts and Significance

The major catalogue bridge companies certainly disliked their loss of primary design influence. Now any big bridge job could simply be let for bidding. The large shops still served other markets in which they retained more design control: rail bridges for smaller carriers and road bridges for local governments. Here too a maker needed close bidding and efficient production to turn a profit. Or the less scrupulous might resort to cheaper metal or bid fixing.[74] Bridge failures did not end after 1880. But they did decline thanks to a range of measures. Beyond the rigorous new routines and standards, other contributing factors included new academically trained engineers, state-level regulation of railway bridge standards and maintenance, improved railway-operating practices, an accelerating move away from wooden bridges, and (after 1890) an increasing preference for steel.[75] By 1890 all the big bridge projects originated with sophisticated design teams employed by independent bridge-financing companies, by railroads, or by governmental agencies (local, state, and national).

The switch from iron to steel accelerated after 1890 as the Siemens-Martin process finally resulted in reliable quality in structural steels.[76] With this new material, civil engineers, the bridge industry, steelworks, and railroads again needed new paradigms for their interactions. Anticipating that need, Theodore Cooper presented an 1879 paper to the ASCE on "The Use of Steel in Bridges." As Cooper wrote his draft, American Bridge was completing the second steel bridge in the country, the Glasgow, Missouri multi-span truss bridge over the Missouri River.

Cooper clearly sought to shape the future, and his key concerns focused on proposing new routines and specifications appropriate for steel. His paper laid down maximum targets for tensile strength and minimal standards for elasticity (as excessive strength produced brittle steels), offering other standards for testing steels for impact resistance. He called for design engineers to physically test steels before use. Those standards would both guide and free steelworks to develop appropriate chemistries and production methods. Throughout, Cooper emphasized the need to develop routines and specifications that would spur a competitive drive to innovate among steelworks, bridge fabricators, and engineers themselves.[77]

 Beyond its narrative of challenges and projects in long-span bridges, this account contributes some ideas of broader significance for our understanding of business, industrial, and economic history. We see that innovation in routines was utterly bound up with innovation in materials and design. Innovative routines may appear to be an oxymoronic term, but the approaches developed by St. Louis Bridge endured because they brought innovators together. Heuristics, specifications, and routines established frameworks for responsibility and cooperation in these joint projects. Historians' emphasis on the paucity of routines for chemical testing of early steel output is perhaps a bit misplaced. What engineers first wanted and got were routines that focused on the physical qualities of steel. It is not just that physical testing was easier than chemical assessments. Tensile strength and elasticity were the measures that mattered for achieving both interfirm cooperation and sufficiently strong bridges.

Bridge building was a classic Scrantonian project-based industry, at least for the long rail crossings over the western rivers.[78] In this field, innovation certainly happened at the level of individual firms—whether it was the Phoenix column, Keystone's Steubenville Bridge, or Eads' choice to use steel chords and shallow arches. But it took a mix of firms to make these projects happen. The heuristics used in the first long-span metal bridges proved adequate to bring firms together to get the jobs done. Then the more formal specifications and routines developed by Eads, Cooper, and the other engineers and firms involved in the St. Louis Bridge became foundations to combine and extend the capacities of individual firms. Advancing professional standards, flexibility in design, and responsibility for the results, those routines in turn sustained innovation over time. To be sure, the new methods hardly guaranteed success. A long cantilever rail bridge over the St. Lawrence River fell during construction in 1907, in a clear case of design failure on the part of

Theodore Cooper himself.[79] Routines could not end human fallibility, but they did reorder this industry across the Gilded Age.

Returning to the frameworks and ideas advanced by Nelson and Winter, these points seem worthy of emphasis. The routines developed in the catalogue bridge industry *circa* 1870 to make pin-connected truss bridges had largely rationalized bridge design and construction, but those routines also motivated fevered price competition in the industry. Firms responded by hawking patented products and by price fixing, outcomes unreckoned by neoclassical economics. Then a contingent accident upset the industry: James p. 203 Eads' desire for a novel arched design and his enlisting of an émigré ↳ design team to make it possible. Those choices were hardly rational in light of the common knowledge and techniques of American civil engineering at the time. But the St. Louis Bridge now has 140 years of use, a testament to the utility of Eads' approaches. The detailed specifications and testing routines pioneered at St. Louis spread quickly in the industry, but not simply out of some deterministic qualities in steel bridges or arch designs. Rather, those new action patterns became widespread practices in the industry as firms and engineers chose to act—motivated by concerns for liability, for managing interfirm relations, and for professionalism. Routines like Cooper's Erie standards or his suggestions for steel specifications did not derive primarily from the profit motive. Rather, they aimed to provide ordered pathways to encourage technological innovation.

Notes

1 The best introduction to American railway bridges in this era is Theodore Cooper, *American Railroad Bridges* (New York: Engineering News Publishing Company, 1889). Another useful source is George L. Vose, *Bridge Disasters in America* (Boston, MA: Lee and Shepard, 1887). The best historical study of design and failure in rail bridges is Mark Aldrich, *Death Rode the Rails: American Railroad Accidents and Safety, 1828–1965* (Baltimore, MD: Johns Hopkins University Press, 2006), chapter 5.

2 A question worth addressing at the start: given that these western-rivers bridges all carried rail traffic, why did independent firms build most of them rather than the carriers, which could have acted directly and owned them outright? That business model had many roots: the railroads were chronically cash poor, an independent firm could hope to sell stock or bonds to local civic leaders and local governments, a railroad's charter often lacked legal authority to build interstate crossings, the promoters behind these ventures hoped to harvest a quick profit akin to those raked in by railway construction firms, and seldom did a single railroad have sufficient traffic to justify its own bridge.

3 For the *locus classicus*, see Richard R. Nelson and Sidney G. Winter, *An Evolutionary Theory of Economic Change* (Cambridge, MA: Harvard University Press, 1982). Routines are the key building block in their theories of evolutionary economics. For subsequent uses and understandings of routines among economists, see Michael D. Cohen, Roger Burkhart, Giovanni Dosi et al., "Routines and Other Recurring Action Patterns of Organizations: Contemporary Research Issues," *Industrial and Corporate Change* 5 (1996): p. 653.

4 Cohen, et al., "Routines," p. 657. For the concept of momentum in technological history, see Thomas P. Hughes, *Networks of Power* (Baltimore, MD: Johns Hopkins University Press, 1983), pp. 15–16.

5 The text below describes Howe trusses in detail. The six spans needed to cross the river at Rock Island had a combined length of 1,581 feet. That example underscores a point in my terminology. A railway "long-span bridge" invariably needed a number of individual spans, supported by a succession of piers, to cross a river. Suspension bridges typically crossed rivers with a single span, but most civil engineers believed that they could not safely bear the heavy moving (dynamic) loads imposed by railway trains.

6 Most details here come from the best source to detail long-span bridges in this era: Gouverneur K. Warren, *Report on Bridging the Mississippi River* (Washington, DC: GPO, 1878).

7 In debate, Cowan denounced corporations generally and the Pennsy specifically, as "exercising a more dangerous and deleterious influence over the politics of the country than all other interests and all other mischiefs combined," *Congressional Globe*, July 7, 1862, p. 3115.

8 Ohio River steamboat men also opposed the draft bill, and secured a navigation-friendly requirement for 90 feet of vertical clearance between river surface and the bridge superstructure. *Appendix to the Congressional Globe* (Washington, DC: GPO, 1862), p. 406. For the love/hate relationship between the PRR and Pennsylvania politicians, see Albert J. Churella, *The Pennsylvania Railroad*, Vol. 1 (Philadelphia: University of Pennsylvania Press, 2013), chapters 3–4.

9 John Piper had headed the Altoona shops of the PRR, Aaron Shiffler was the line's general bridge supervisor, while a third partner in the start-up firm, Jacob Linville, was a PRR bridge designer. Beyond those three men, the partnership of Piper and Shiffler included the PRR president (Edgar Thomson), its vice president (Tom Scott), and Scott's young assistant and man on the make (Andy Carnegie).

10 The longest river in North America (2,341 miles), the Missouri drains a watershed of 500,000 square miles. Rains, snows and snowmelt, freezes, and droughts across ten U.S. states and two Canadian provinces affect its flow.

11 Beyond sources in note 1, the catalogue bridge industry and its products are described in Victor C. Darnell, *Directory of American Bridge-Building Companies, 1840–1900* (Washington, DC: Society for Industrial Archaeology, 1984); Eli Wood Imberman, "The Formative Years of Chicago Bridge and Iron Company," (Ph.D. dissertation, University of Chicago, 1973); and Thomas R. Winpenny, *Without Fitting, Filing, or Chipping: An Illustrated History of the Phoenix Bridge Company* (Easton, PA: Canal History and Technology Press, 1996). For a typical trade catalogue, see Keystone Bridge Company, *Descriptive Catalogue of Wrought Iron Bridges* (Philadelphia, PA: Allen, Lane, and Scott, 1874), available at <http://www.hathitrust.org>. According to an authoritative source, the catalogue bridge industry numbered over forty firms in 1888, with at least twelve capable of designing and building crossings of any size or complexity (Cooper, *American Railroad Bridges*, pp. 35–6).

12 It may be helpful to give a little more detail. The contract shops served three markets: independent bridge-financing/operating companies ordering long-span railway crossings, railroads needing many semi-standard bridges for routine crossings of streams and streets, and local governments purchasing common roadway bridges. Price competition was one concern among many in long-span rail bridges, given their specialized design and strength requirements. Railroads wanted competitive pricing for their common bridges. The contract shops could make these specialized products cheaper, better, and faster than could most railroads. City and county governments generally wanted cheap bridges, and few had the technical capacity to judge quality, although by the Gilded Age the largest American cities typically had staff engineers.

13 Eda Kranakis, *Constructing a Bridge* (Cambridge, MA: MIT Press, 1997).

14 "Autobiography of Grenville M. Dodge," typescript, p. 1068, Dodge papers, State Historical Society of Iowa.

15 In wooden truss bridges *circa* 1830, a designer/builder commonly used lumber of the same cross-section throughout the span, as wood was cheap (often cut on site), custom cutting was dear, spans were short, and stresses unknown. Once they adopted more expensive iron, however, builders could specify heavier scantlings (cross-sections and other proportions) where they needed strength, with lighter components when they sought economy of weight and cost (Cooper, *American Railroad Bridges*, p. 22). In switching from wood to iron, engineers could and did calculate the stresses and loadings on individual components more thoroughly. Wood was cheap, liable to unknown interior flaws, and began decaying immediately—all arguments to rely on brute strength. Iron was comparatively expensive, while its structural integrity was knowable, and its load-bearing abilities within reasonable calculation, especially as the iron mills improved their workmanship.

16 The qualities of different truss types—Howe, Fink, Bollman, Warren, and countless others—mattered a lot to nineteenth-century engineers and to historical specialists. In this context, however, only three points are important. The railroads' increasing demands upon bridges encouraged the shift to all-metal structures. The potentials in iron bridges motivated engineers to develop new types. By patenting them, the contract bridge shops hoped to gain some shelter from price competition. For example, American Bridge hawked its specialty, Post's patented truss bridge.

17 Any bridge typically has parts that are in tension (a pulling action) with other components in compression (squeezing). In truss bridges, the horizontal beam at the top (the top chord) is always in compression; the bottom chord is in tension. Angled braces connect the two chords to create a truss: "struts" bear compression loads, while "ties" are in tension. Bridge builders of the 1840s first used iron for ties as its structural nature made it better suited (than wood) for tension loads.

18 See the entry on Howe in *A Biographical Dictionary of Civil Engineers* (New York: American Society of Civil Engineers, 1972), p. 63.

19 "American Bridge Company," *Railroad Gazette* 3 (July 29, 1871), p. 201. Throughout, the text will refer to Boomer's firm by its 1870 name of American Bridge.

20 "Phoenixville Bridge Works," *Railroad Gazette* 4 (March 2, 1872), p. 100.

21 Henry Grattan Tyrrell, *History of Bridge Engineering* (Chicago: HardPress Publishing, 1911), p. 178.

22 For example, American Bridge had a standing contract from the Union Pacific to supply its needs for short bridges (mostly wooden) in its dash across the plains. Maury Klein, *Union Pacific*: *Birth of a Railroad, 1862–1893* (New York: Doubleday, 1987), p. 81. In the unique market for long-span rail bridges, the terms of trade included competitive pricing, delivery speed, reputation for quality, credit terms, and personal/professional ties.

23 In the 1880s, civil engineers George Vose, George Thomson, and Charles Stowall denounced the safety record of American bridges, while Theodore Cooper mounted a defense (Aldrich, *Death Rode the Rails*, pp. 145–51). Some engineers saw in the debate a chance to press the U.S. government to conduct costly strength testing of iron and steel. Some sought state-

level regulatory oversight to stem failures, while others feared regulation. Some independent consulting engineers hoped to advance their own status and business by denouncing the products of the catalogue bridge shops (my thanks to D.C. Jackson for raising this point which he explored in "19th Century American Bridge Failures: A Professional Perspective," *Proceedings of the 2nd Historic Bridges Conference* (Columbus: Ohio State, 1988)). As Aldrich notes (*Death Rode the Rails*, chapter 5), failure itself was a complex phenomenon, variously rooted in design, construction, and maintenance of bridges—and in railway operations and management.

24 Cooper, *American Railroad Bridges*, p. 22. The live loading represented a moving train; by 1870, a 30-ton locomotive typically hauled freight cars totaling 200 tons. The weight, however, was distributed across all the wheels in the train. In turn the bridge's structure further distributed the momentary weight or loading imparted by each wheel. These operational facts made feasible a specification that the bridge bear 2,500 pounds of live load across every lineal foot of its length. Nonetheless, such a "uniform loading" specification was a primitive approximation and a gross simplification of the forces and loads that such a train actually imparted (discussed further below).

25 Alfred Boller, "Papers on Bridge Construction," part 5, *Railroad Gazette* 4 (March 2, 1872), p. 91.

26 This design method is described in "Proceedings and Report of the Board of Civil Engineers Convened in St. Louis in August 1867," chapter 3 (St. Louis, 1867), which reflects the practice at American Bridge. Also see Cooper, *American Railroad Bridges*, pp. 21–2.

27 In October 1868, the young Washington Roebling wrote a detailed description of machinery and methods at Keystone Bridge. Keystone had an average of twenty/twenty-five bridges in fabrication at any time, with forty-four underway in Fall 1867. In Roebling's words, "as the profit is small, they can only make it pay by having many in hand" and by routinizing every step. Washington Roebling to John A. Roebling, October 11, 1868. Roebling Papers, Rensselaer Polytechnic Institute.

28 For simplicity's sake, this account leaves out the process of building foundations for these bridges: the abutments at each end, the piers that supported trusses in the river, and the underlying pilings or caissons that supported the piers and abutments. The contract bridge shops often declined this work, leaving bridge-financing companies to make their own local arrangements.

29 Edward Howland, "Iron Bridges, and Their Construction," *Lippincott's Magazine* (January 1873): p. 22. The superstructures came together quickly thanks largely to their pin connections.

30 "Test of the Keokuk and Hamilton Bridge," *Railroad Gazette* 3 (July 15, 1871): p. 178.

31 Describing design practices circa 1870, Theodore Cooper wrote "Though many excellent bridges, considering the state of the art, were built under this system, there were also many very inadequate structures made" (*American Railroad Bridges*, p. 22).

32 Cohen et al., "Routines," pp. 657, 663.

33 Robert B. Gordon, *American Iron, 1607–1900* (Baltimore, MD: Johns Hopkins University Press, 1996), p. 200.

34 Alfred Boller, "Papers on Bridge Construction," part 1, *The Railroad Gazette* 4 (February 3, 1872): p. 48.

35 For example, the project to build the St. Charles (Missouri) crossing of the Missouri River (under Shaler Smith) shared much experience and many design choices with the design team working on the St. Louis bridge under James Eads. See "The St. Charles Bridge," *Railroad Gazette* 3 (July 8, 1871): p. 169.

36 These details from Warren, *Report on Bridging the Mississippi River*, pp. 117–21.

37 John K. Brown, "Not the Eads Bridge: An Exploration of Counterfactual History of Technology," *Technology and Culture* 55(3) (July 2014): pp. 521–59.

38 James Eads had three reviews—by Jacob Linville, Junius Adams, and James Laurie. A competing bridge proposal at St. Louis, advanced by Lucius Boomer, was reviewed by a panel of twenty engineers. Later that year, some of those men convened to consider John Roebling's plans for Brooklyn. In one sense, these reviews were elaborate window dressing, aimed primarily at investors. Yet they also helped develop design concepts across the profession.

39 Cohen et al., "Routines," section 4.

40 Thomas Curtis Clarke, *An Account of the Iron Railway Bridge across the Mississippi River at Quincy Illinois* (New York: Van Nostrand, 1869), Octave Chanute, *The Kansas City Bridge* (New York: Van Nostrand, 1870).

41 "The Kansas City Bridge," *Railroad Gazette* 3 (May 27, 1871): p. 100.

42 Inadequate design and specification for highway bridges was a real problem, largely because the local authorities who ordered these spans had little engineering knowledge, but much pressure to keep costs down. For more on these points, see James B. Eads, C. Shaler Smith, Thomas C. Clarke et al., "On the Means of Averting Bridge Accidents," *Transactions of the American Society of Civil Engineers* 4 (1875): pp. 122–35.

43 For example, ASCE engineers recommended that common roadway bridges in manufacturing districts be proportioned to carry a load of 100 pounds per square foot if the bridge was less than 60-foot long. But they set a maximum loading (per square foot) of 75 pounds for bridges 100–200 feet in length (see Eads et al., "On the Means of Averting Bridge Accidents," p. 123).

44 Alfred Boller, "Papers on Bridge Construction," part 1, *Railroad Gazette* 4 (February 3, 1872): p. 48; part 2 (February 10,

1872): p. 61; and part 5 (March 2, 1872): p. 91.

45 See Brown, "Not the Eads Bridge," for details on the competing designs of Boomer and Eads.

46 Designed by Philadelphia city engineer, Strickland Kneass, the Chestnut Street bridge was a bold exploration of another new material, cast iron, in a daring span length of 184 feet. Thereafter cast iron fell into disrepute for structures.

47 At Koblenz, the arches were 317-foot long. They carried a double track railway (as at St. Louis) but no roadway deck.

48 Calvin Woodward, *A History of the St. Louis Bridge* (St. Louis, 1881), p. 16.

49 Trusses, by contrast, were determinate structures, easy to design and analyze with trigonometry. For a discussion of determinate versus indeterminate bridge designs in this era, see Carl W. Condit, *American Building Art: The Nineteenth Century* (New York: Oxford University Press, 1960), pp. 190–5.

50 Why was Eads so determined to break with orthodox design? All accounts root the explanation in his working career on the river. To Eads, the primary design challenge for any bridge at St. Louis lay in building secure piers, structures that would reliably withstand the powerful forces embodied in flood currents, winter ice jams, and riverbed erosion. That judgment call in turn caused Eads to specify just two river piers, built massively in stone, supporting spans of record length.

51 Woodward, *A History of the St. Louis Bridge*, chapter 26.

52 Howard Miller and Quinta Scott, *The Eads Bridge* (Columbia: University of Missouri Press, 1979), p. 96.

53 Casimir Constable, "Arched Beams," *Transactions of the American Society of Civil Engineers* 1 (1871): p. 376.

54 Miller and Scott, *The Eads Bridge*, p. 95.

55 Miller and Scott, *The Eads Bridge*, p. 95.

56 Herman Haupt, *General Theory of Bridge Construction* (New York, 1851), p. 62.

57 Alfred Boller, "Papers on Bridge Construction," part 1, *Railroad Gazette* 4 (February 3, 1872): p. 48.

58 Woodward, *A History of the St. Louis Bridge*, pp. 293–5.

59 Woodward, *A History of the St. Louis Bridge*, p. 68.

60 Butcher's struggles in producing the steel for St. Louis Bridge are described by Miller and Scott, *The Eads Bridge*, pp. 110–18; by Geoffrey Tweedale, *Sheffield Steel and America* (Cambridge: Cambridge University Press, 1987), pp. 114–16; and by Robert Kanigel, *The One Best Way* (New York: Viking, 1998), pp. 153–7.

61 Woodward, *A History of the St. Louis Bridge*, p. 297.

62 Woodward, *A History of the St. Louis Bridge*, p. 71.

63 For a resume of Cooper's career, see William D. Middleton, *The Bridge at Quebec* (Bloomington: Indiana University Press, 2001), chapter 3.

64 The Rock River bridge failure is described in "Scenes and Incidents after the Terrible Accident at Rock River Bridge," *Frank Leslie's Illustrated Newspaper* (May 24, 1873): p. 173. The Ashtabula disaster and its aftermath are described in Henry Petroski, *Engineers of Dreams* (New York: Knopf, 1995), pp. 96–7.

65 Eads et al., "On the Means of Averting Bridge Accidents," pp. 122–35.

66 Amasa Stone, Jr. was the brother-in-law of William Howe, the inventor/patentee of the Howe truss (1840). Another Howe brother-in-law, Andros Stone, had been Lucius Boomer's partner in a Chicago bridge-building firm, Stone and Boomer, until it dissolved in 1857 (Darnell, *Directory of American Bridge-Building Companies*, p. 83).

67 "The Ashtabula Disaster," *Engineering News* 4 (March 17, 1877): p. 67.

68 Aldrich, *Death Rode the Rails*, p. 143. That dollar figure equaled the purchase price of 100 new locomotives.

69 Writing in 1889, Theodore Cooper clearly saw the Ashtabula failure as a key turning point in railway bridge design (*American Railroad Bridges*, pp. 23–4) as does Aldrich (*Death Rode the Rails*, pp. 143–4). In December 1879, an eighteen-month-old iron truss bridge in Scotland, the Tay Bridge, failed catastrophically, a further warning to American designers.

70 "Western Union Railroad," *Engineering News* 5 (January 31, 1878), pp. 40, 49–50. The publication of such specifications was another important development, promoting acceptance of standard routines across railway companies, bridge builders, and structural iron makers.

71 Cooper, *American Railroad Bridges*, p. 24.

72 Tyrrell supports this portrait, saying that until 1875 or so, the bridge fabricators normally developed full designs, they received "lump sum contracts," and they thus tended to skimp on metal and strength. After that date, he finds a broad trend of railroads insisting on their own standard specifications for bridges (*History of Bridge Engineering*, p. 178).

73 Chandlerian business history emphasizes the roles of trained managers (and their professional societies and associations) in shaping modern corporations, a development that Alfred D. Chandler, Jr. traced to American railroads of the mid-nineteenth century. See *The Visible Hand: The Managerial Revolution in American Business* (Cambridge, MA: Harvard University Press, 1977).

74 Imberman's fine dissertation explores the widespread use of bid fixing in the contract bridge industry. See his appendix I.

75 Aldrich, *Death Rode the Rails*, pp. 151–4.

76 Tyrrell, *History of Bridge Engineering*, p. 171.

77 Theodore Cooper, “The Use of Steel in Bridges,” *Transactions of the American Society of Civil Engineers* 8 (1879): pp. 263–94.

78 Philip Scranton, “Projects as a Focus for Historical Analysis: Surveying the Landscape,” *History and Technology* 30 (2014), pp. 354–73.

79 Middleton, *The Bridge at Quebec*, book 1.