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ABSTRACT

This paper is an excerpt from a larger book project called *The Corporation and the Twentieth Century*, which chronicles and interprets the institutional and economic history – the life and times, if you will – of American business in the twentieth century. One integrating theme of the book is that the signal calamities of the Great Depression and World War II, as well as the policy responses to those calamities, are crucial in understanding the structure of American industry in the post-war world. This excerpt examines the role of research and development in the corporation before and during the Depression. It argues that, although corporate R&D labs did generate many important new technologies, innovations also flowed importantly from a large variety of other sources, both within the corporation (but outside of the research lab) and elsewhere in the economy. Even though corporate research did sometimes lead to new products for the corporation to exploit, a narrative in which internal R&D systematized innovation widely in the service of corporate diversification is on the whole a fable. Nonetheless, by destroying market-supporting institutions (including, importantly, sources of external finance) and by reducing the information content of price signals, the Depression did help solidify the nexus between R&D and the large corporation. Coupled with New Deal price and entry regulation in many sectors, and followed by the far greater extent of non-market controls during World War II, the Depression set the stage for the emergence of the large Chandlerian corporation of the post-war period.

JEL: D23, L51, L52, L6, L9, N42, N62, N72, N82, O3, P12, P16
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The Great Depression severely hampered the ability of the price system to allocate resources effectively. Especially during the years of contraction, the price system was all but destroyed. Through a number of mechanisms, this gave advantage to larger firms, which were able to allocate resources, crucially including capital resources, internally. At the same time, the unintended if not intended consequences of New Deal policies favored large firms over smaller ones on the whole (though with some exceptions) and worked to further muddle relative prices after 1933. The Depression-era distortion of relative prices and the accompanying destruction of market-supporting institutions, soon to be followed by the imperatives of a war economy, would set the stage for the emergence of the large Chandlerian corporation of the post-war world.

As we saw, the debt-deflation of the contraction phase between late 1929 and late 1933 had adverse real effects on the economy. Prominent among these was an increase in the real cost of borrowing on external financial markets.[1] Deflation worsened the financial position of businesses by raising their expenditures for short-term debt while lowering the value of their collateral; these firms saw their sales revenue plummet, but could do little about their fixed costs. All of this diminished the creditworthiness of these firms in the eyes of banks and other external sources of funds, which as a result demanded higher rates or refused to loan at all. At the same time, banks felt their own cost of capital increase as deposits evaporated, and the supply of loans decreased accordingly. Banks tended to engage in selective rationing of loans, meaning that external financing was even less available than the prevailing high real interest rates would suggest. Faced with declining

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[1] Bernanke and Gertler (1995); Calomiris and Hubbard (1990).

cash flow, businesses were forced to cut production and employment, and of course many closed down. By contrast, the largest firms were able to *increase* their cash-to-receipts ratios as both sales and receipts fell.[2] Indeed, the cash holdings of American firms increased some two-and-a-half fold between the early 1930s and the mid-1940s.[3] This cash was concentrated in the largest firms, reflecting an attempt to accumulate precautionary savings in a highly uncertain macroeconomic and political environment. Because there was virtually no stock issue during this period and debt was being retired, retained earnings accounted for more than 100 per cent of financing for the American corporate sector as a whole.[4]

During the contraction phase of the Depression between late 1929 and late 1933, output and employment fell both because many firms were driven out business and because most of the firms that survived produced less and employed fewer workers. Hardest hit were businesses that made long-lasting products, whether capital goods or consumer durables. Sectors that produced more-ephemeral products like food, tobacco, and petroleum products suffered a milder decline than average and recovered more quickly.[5] Automobiles and radios, two of America's high-tech growth industries in the twenties, suffered declines much worse than the economy-wide average. Over this period, the real value of manufacturing output in the U. S. fell something like 40 per cent; in automobiles

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[2] Hunter (1982, p. 884).

[3] Graham and Leary (2018, p. 4296). After the war, cash holdings slowly returned to pre-Depression levels by about 1970.

[4] Calomiris and Ramirez (1996, p. 157).

[5] Bernstein (1987, p. 53).

it fell 60 per cent, and in radios and phonographs it fell 80 per cent.[6] In automobiles, there were only 58 per cent as many establishments in 1933 as there had been in 1929; in radio, there were only 46 per cent as many.

"Liquidationists" like Andrew Mellon saw this destruction as largely creative: the Depression was weeding out the relatively less-fit plants and firms. In both industries, there was in fact considerable heterogeneity among establishments in size, technology, organization, and measured productivity. Using data from the Census of Manufactures, Timothy Bresnahan and Daniel Raff examined in detailed the shakeout in automobiles.[7] They found that unemployment was disproportionately the result of plant closings. Plants that continued to operate during the downturn, they believed, were those that had adopted mass-production techniques and thus had lower average costs.[8] More recent research has revisited the data and called into question whether selection was operating so clearly on efficiency.[9] At least in the passenger-car segment, it appears that sheer size was a far more important filter than productivity, and this mechanism operated through the greater ability of larger outfits to obtain financing. The evolutionary process was not symmetric: although the decline witnessed large-scale exit, the resurgence of the industry after 1934 was accomplished by growth within the surviving firms rather than by significant entry of new

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[6] Bresnahan and Raff (1991, pp. 320-321); Scott and Ziebarth (2015, p. 1103).

[7] Bresnahan and Raff (1991`).

[8] This was so even though continuing plants had lower-than-average labor productivity, probably because they rendered unemployed fewer workers relative to output declines than did failed firms. The larger firms were engaging in "labor hoarding."

[9] Lee (2015).

firms. "Already by 1935, the auto industry resembled its postwar self: a standing body of mass-production plants with quasi-permanently affiliated management and labor."[10]

Peter Scott and Nicolas Ziebarth carried out a similar exercise for the radio industry and found a similar pattern of shakeout, albeit with some crucial differences.[11] In automobiles, the largest firms like GM, Ford, Chrysler, and Hudson tended to be the ones that produced high volumes using mass production, whereas smaller firms tended to cater to higher-end tastes using costlier production processes. In radio, it was the reverse, with smaller firms typically targeting the low-price segment and larger firms – centrally RCA – producing more upscale devices at higher prices. This was because, as we saw, the radio was a far more modular product than the automobile, and this enabled producers to lower costs through vertically disintegrated chains of supply and distribution. As there were essentially no economies of scale in radio assembly, economies of scale could not be the criterion of selection. Instead, the firms that tended to survive were the ones that cultivated their own distinctive brand along with a curated network of suppliers and distributors. Those with a less-developed network, including firms that operated as original-equipment manufacturers for department stores and other branders, were overrepresented among the entities selected out. Creating a brand and cultivating relationships with suppliers are investments that imply fixed costs; and firms bearing such costs were more likely to continue to produce so long as they could (mostly) cover their variable costs. For firms without branding and network investments, exit was a cheaper option.

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[10] Bresnahan and Raff (1991, p. 329).

[11] Scott and Ziebarth (2015).

In an sense, of course, the automobile and radio industries reacted in a similar fashion to the catastrophe of the Depression. Like American industry in general, they largely turned from a business of making standardized durables at increasingly lower cost to a business of making new and distinctive products. As many have suggested, the annual model change could be understood in exactly this way – as a mechanism for making the automobile a more-ephemeral product.[12] Already underway at GM in the twenties, the annual model change became institutionalized across the industry in the thirties. This was thanks in part to the NRA, whose automobile code standardized to autumn the timing of the change for all firms, a coordination equilibrium that would long survive the agency's demise.[13]

Alexander Field has pointed out that, contrary to what most imagine, the Depression era may well have been the most technologically progressive decade of the century in the United States.[14] The rate of growth of total-factor productivity over the period rivaled, and by some estimates exceeded, that of any other decade.[15] Although the shakeout in American industry sometimes tended to select for size and cohesion rather than for productivity, the Depression nevertheless set in motion a technological revolution in industry. Field offers two mechanisms for this resurgence.[16] The first is the rapid growth of research and development within American industry. Even during the downturn, the

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[12] Bernstein (1987, pp. 134-135).

[13] Cooper and Haltiwanger (1993).

[14] Field (2012).

[15] See also Bakker *et al*. (2017) and Watanabe (2016).

[16] He also cites the supply-side benefits of the build-out of the U. S. highway system in the twenties. I return to this in the context of rail and trucking below.

number of scientists and engineers employed in manufacturing continued to increase, from 6,272 in 1927 to 10,918 in 1933.[17] By 1940 the number was 27,777. The second mechanism Field identifies is *adversity*, the imperative to change and reorganize in the face of catastrophe.

These mechanisms are not as distinct as they may seem, especially if we think about research and development in the right way. In their formal models, economist tend to think of R&D as a specialized stage of production that combines inputs, notably including skilled labor, to manufacture a distinctive good called "knowledge." This good then becomes an input to the production of other goods; but, unlike ordinary inputs, knowledge operates exclusively to increase the effectiveness of all the other inputs and thus to lower costs of production.[18] Although this is for many purposes an insightful way to think about the knowledge-generation process, if taken literally it seriously mischaracterizes the nature and function of research and development in industry. As we have seen repeatedly, both firms and markets are themselves mechanisms of knowledge generation. With their very different organizational structures, both Ford and GM were learning organizations in the years before the Depression; the network of independent suppliers was also a learning ecosystem. Research and development must be understood as one part – not the only part – of the firm's (and the market's) ability to learn.

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[17] Field (2012, p. 56).

[18] In these models, product innovation is compressed into process innovation. Whereas process innovation is the ability to produce an existing product at lower costs, product innovation is represented as the ability to extract greater value from an existing product without increasing costs. Paul Romer recently won a Nobel Prize for thinking about the production of knowledge in this way. See for example Romer (1994).

Students of the history of technology have long derided what they call the linear model of R&D, in which knowledge is created *ex nihilo* in a research lab, gets handed off to development, and then gets handed off to production. The elements of the process are actually far more intertwined, and the R&D function exists in significant part as a resource for solving problems on the ground within the firm, not as a font of new ideas. In many cases, it is only when the technological problems the firm faces become refractory to existing capabilities that the organization attempts to delve deeper into the underlying scientific principles, only then – and not always even then – generating a more formal commitment to scientific research.[19] "The advantages of placing R&D within the firm reflect the fact that the sources of many commercially valuable innovations do not lie in scientific laboratory research," writes David Mowery. "Instead, much of the knowledge employed in industrial innovation flows from the firm's production and marketing activities."[20] In this respect, the increased recourse to R&D during the Depression was simply one face of the response to adversity.

Although the number of scientists and engineers employed in R&D rose during the period 1927 to 1933, an absolute increase of 4,500 people isn't likely to have had a significant impact on nationwide total-factor productivity. Indeed, in the original 1960s calculations by John Kendrick on which Field relies, TFP actually *fell* at a rate of three per cent per year over the period 1930-1933 – a significant technological regression.[21] Recent

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[19] Hoddeson (1981, p. 516).

[20] Mowery (1995, p. 149).

[21] Kendrick (1961).

estimates think that TFP growth in those years was positive but low.[22] According to a National Research Council survey of industrial research laboratories in 1933, corporate spending on research and development had held steady through 1931 but fell in both 1932 and 1933.[23] In both of those years, more firms were cutting budgets than raising them or keeping them constant. In 1932, average spending on R&D fell by 27 per cent. There is also evidence from patents that innovative efforts became less risk-taking and less original in this period, a phenomenon linked to bank distress and the high cost of external finance.[24]

By all calculations, it was not until after 1933 that the takeoff in productivity began. And it was also during the post-1933 period that research and development, and the industrial R&D lab, came into its own as part of industry's response to the Depression. In the early twentieth century, innovation had been driven importantly by individual entrepreneurs operating within a thriving market for intellectual property.[25] These inventors sold their patents, or sometimes sold what amounted to small startups, to firms that could further develop their ideas. During the 1920s, smaller enterprises that developed or acquired technology could avail themselves of increasingly well-functioning securities markets as well as of what we would now recognize as venture capital.[26] Regional securities exchanges were especially important for these small firms. Centralized corporate research labs were beginning to spring up, but these were concentrated in the mid-Atlantic states, where science-oriented industries like chemicals and electrical equipment were

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[22] Watanabe (2016, p. 919).

[23] Holland and Spraragen (1933, p. 2).

[24] Nanda and Nicholas (2014).

[25] Lamoreaux and Sokoloff (1999).

[26] Lamoreaux *et al*. (2011).

located; the East-North-Central states, which tended to produce complex-systems products like the automobile, remained the province of the independent inventor-entrepreneur.[27] One of the central functions of a corporate research lab has always been to keep abreast of relevant technology and to scan the horizon for new ideas generated outside the firm, often with an eye to acquiring the resulting patents.[28] In the 1920s, a significant number of the most valuable patents held by large firms originated outside those firms's own R&D labs.[29]

As bank distress raised the cost of external financing after 1929, and as the Securities Exchange Act of 1934 imposed higher costs on regional securities exchanges, the market-based network of inventor-entrepreneurs found its access to funding diminished. Larger firms, many of which possessed formal R&D labs, fared much better. The East-North-Central states, which relied heavily on the system of independent inventors, were affected more adversely than the mid-Atlantic states, where formal R&D labs were prevalent.[30] Measured in terms of relative employment of technical personnel, small firms continued to be as research intensive as large firms, and they continued to benefit from R&D.[31] But those of the largest firms that maintained formal R&D functions were better able than those without labs to maintain their rankings in the league tables of America's top 200 firms, probably both because R&D contributed to profitability and because those firms that were generally better able to survive the forces of the Depression

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[27] On the distinction between science-based products and complex-systems products, and the importance of this distinction for intellectual property rights, see Merges and Nelson (1990).

[28] Cohen and Levinthal (1989).

[29] Nicholas (2009).

[30] Lamoreaux *et al*. (2011).

[31] Mowery (1983).

were also the ones more able to afford R&D labs. Significant new patents started to emerge increasingly from corporate labs. "Large firms would come to dominate technological discovery more completely over the middle third of the century, but contrary to the standard literature, the change was more a result of the differential effect of the Great Depression than of the inherent superiority of in-house R&D."[32]

As the Depression reoriented firms away from mass production and toward greater emphasis on product innovation and branding, research and development likewise redirected its focus. "There has been a decided change in the object of research during the past four years," declared the National Research Council survey in 1933.[33] "In 1928, the major emphasis was upon the lowering of production costs. In 1931, it was on the development of new products and increasing the quality of existing products." As we have seen, once a product becomes relatively standardized, the business of making the product more cheaply does not necessarily advantage the large firm or implicate vertical integration. Standardization renders innovation relatively *autonomous*, meaning that technical change is able to proceed within established design boundaries; this in turn means that the innovative process can take advantage of a diverse array of independent sources, leading to rapid trial-and-error learning.[34] By contrast, creating new products often requires *systemic* innovation, combining or recombining elements in a way that supersedes existing design boundaries and destroys existing pathways of supply and distribution. Even

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[32] Lamoreaux *et al*. (2011, p. 236).

[33] Holland and Spraragen (1933, p. 3).

[34] Baldwin (2008); Langlois (1992); Nelson and Winter (1977); Teece (1986).

systemic innovation can take place through the price system in some cases.[35] Yet there clearly can be transaction-cost advantages to executing systemic innovation (mostly) within a single organization, where owners or managers can exercise fiat and where a central research laboratory can provide bureaucratic space to test out new configurations. This is especially true – and here, of course, is the point – when, as during the Great Depression, the alternative of negotiating systemic change through the market is impeded by high costs of external finance, by the wholesale elimination of potential trading partners, and by the unreliability of price signals.

For Alfred Chandler, the emergence of the corporate R&D lab was closely tied to the organizational innovation of the multidivisional structure. And, for the most part, we do not observe a genuinely effective central lab in firms that have not also created a strong central office.[36] Like a central office, in which executives are freed in principle from day-to-day operational concerns in order to engage in long-range strategic thinking, a central research lab provides a sheltered sphere in which researchers can in principle look ahead unimpeded while providing services that spill over to multiple divisions. As with the M-Form more generally, of course, what was true in principle worked differently in practice, and it became a thorny problem of management to keep the (often geographically isolated) technical staff adequately plugged into the knowledge and needs of the divisions and to provide the right kinds of incentives to keep the researchers focused on corporate goals.[37]

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[35] For example, as we shall see, in the case of the personal computer. In order for systemic innovation to proceed through market interfaces, the design involved has to be relatively modular and the market has to be dense and sophisticated enough to provide the necessary components.

[36] Mowery (1981, p. 113).

[37] Lamoreaux *et al.* (2011); Mowery (1995).

When the multidivisional research system is working smoothly, the result is a process of internal product diversification. In Chandler's account, as in the related account of Edith Penrose, diversification occurs when a firm finds itself with excess capacity, which could be literal production capacity or more intangible excess resources like management knowledge.[38] The job of the lab is to find new products over which the fixed costs of the excess capacity can be spread. If the lab comes up with a product that doesn't fit well with the firm's capabilities, the technology might be licensed to the market. In general, however, the firm will simply add the new product to its portfolio, slotting it in within an existing division if it fits well enough but creating a whole new division if it does not. "The multidivisional structure adopted by General Motors, Du Pont, and later by United States Rubber, General Electric, Standard Oil, and other enterprises in technologically advanced industries institutionalized the strategy of diversification," wrote Chandler. "In so doing, it helped to systematize the processes of technological innovation in the American economy."[39]

That the large multidivisional firm systematized the process of technological innovation was of course a foundational contention in twentieth-century discourse about the corporation. It provided a crucial refinement to the longstanding Progressive claim that salaried professionals could scientifically plan production: now they could even create *new* products, more or less at will. But what Chandler (and Penrose) fail to emphasize is that whether it is cheaper to produce a new product internally or license that product depends not only on the internal capabilities of the firm but also on the capabilities of "the market"

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[38] Penrose (1959).

[39] Chandler (1977, p. 467).

– which is to say, on the capabilities of other firms that might potentially take up the technology. A well-functioning market will provide far more opportunities to unload a new technology profitably than will a poorly functioning one. And a well-functioning market has mechanisms in addition to internal diversification for generating new products and processes, notably startups and spinoffs, both of which operated extensively before and after the Depression. In the trough of the Depression, however, markets were *not* functioning well, and internal diversification by large firms would indeed be a central mechanism of innovation during the recovery. As Chandler himself rightly noted, the Depression created rampant excess capacity, and firms moved to take advantage of that capacity by generating new products.[40]

In the period from 1921 through 1946, the most research-intensive sector of manufacturing was chemicals, the prototypical science-based industry.[41] And dominating chemicals was E. I. du Pont de Nemours & Company, which was in turn the prototype of Chandler's model of research-driven diversification. Already before World War I, Du Pont had begun diversifying in response to major episodes of excess capacity in smokeless-powder production. In 1908, the military canceled a major order, and two years later the Army and Navy both built up their internal production capacity in response to Congressional hostility to Du Pont.[42] The company responded by developing other products, like artificial leather and the organic substance pyroxylin, which could be made with the same cotton-based nitrocellulose technology as smokeless powder. The war

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[40] Chandler (1962, p. 44).

[41] Mowery (1983, p. 964).

[42] Chandler (1962, pp. 79-83).

quickly put an end to excess capacity, while forcing diversification of a quite different kind. Du Pont found it needed to produce internally many of the inputs it had once bought on the market as well as to supply products, notably dyes, that had been German specialties. After the war, the company was thus left with an impressive array of excess capabilities, including know-how, physical facilities, and cash, for which it began seeking uses in the production of peacetime products. “Such exploration,” wrote Chandler, “would transform the Du Pont Company from the nation’s largest explosives manufacturer into its largest chemical producer.”[43]

Yet this diversification was not driven by internal science or invention, let alone by the company’s central research lab, which did not begin to take shape until 1924.[44] Almost all of the diversification took place through acquisition. This was a period of scientific ferment in chemistry, during which chemical technology was evolving rapidly, especially in Europe. Ideas were there for the taking. During the 1920s, major new products like viscose rayon, tetraethyl lead, and cellophane were produced by Du Pont but invented elsewhere.[45] The company’s most important excess resource was actually its ability to sell to the huge American market. Taking advantage of its experience in manufacturing, the company positioned itself as a supplier of basic organic chemicals and related products, and it largely refrained from integrating backward into feedstocks or forward into final

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[43] Chandler and Salsbury (1971, p. 381).

[44] Hounshell and Smith (1988, pp. 119-123).

[45] Mueller (1962). The company did accidentally invent what became Duco enamels for automobiles, and it put concerted effort into developing a moisture-proof version of cellophane.

products. This all required extensive adaptation and technology transfer to customers, of course, but in the end that was a matter of development not research.

Between 1929 and 1933, Du Pont sales plummeted nearly 50 per cent. Except for a 20 per cent cut in 1931-32, however, the company maintained its level of expenditure on R&D.[46] In tune with the spirit of the times, Lammot du Pont, the company president, declared a policy of "refinement" not retrenchment in research, meaning "elimination of the weaker employees."[47] This the company did.

In 1927, at the instigation of research director Charles M. A. Stine, the Du Pont board had approved the creation of a fundamental research program within Stine's Chemical Department, the largest of the company's decentralized research units. Stine's argument was that existing research facilities were too busy doing scutwork for the production departments. What was needed was a capability to "invent some good, *big*, profitable things."[48] Funded at $25,000 a month through 1929, the program was able to store up a reserve that tided it over the worst years of the Depression without a reduction in expenditure.[49] Stine attracted away from Harvard the brilliant but troubled polymer chemist Wallace H. Carothers to head the program.[50] Drawing on academic research by Father Julius A. Nieuwland at Notre Dame, by 1931 Carothers's group had invented neoprene, the first general-purpose synthetic rubber.[51] Although more expensive than

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[46] Hounshell and Smith (1988, p. 287).

[47] Hounshell and Smith (1988, p. 313).

[48] Hounshell and Smith (1988, p. 135), emphasis original.

[49] Hounshell and Smith (1988, p. 242).

[50] Carothers suffered from severe depression and committed suicide in 1937 at age 41.

[51] Mueller (1962, p. 333).

natural rubber, neoprene possessed a number of desirable properties, including resistance to petroleum products, which earned it a profitable niche market.

But the best, biggest, and most profitable thing was to be nylon, whose discovery and commercialization became the paradigm of the linear model of R&D. As a producer of rayon, Du Pont was on the lookout for new artificial fibers, and this became one focus of the Carothers lab. In the same month as the discovery of neoprene in 1930, one of Carothers's assistants was cleaning out a reaction vessel when he noticed that a promising superpolymer had formed.[52] Over the next five years, the lab worked, through trial and error, to find a similar polymer that would be suitable as a commercial fiber. At one point, Carothers temporarily gave up. But on February 28, 1935, the lab synthesized polymer 6-6, which would become nylon. Learning to mass produce the new fiber turned out to be a systemic development problem, for which Du Pont could draw on existing internal capabilities, especially in its ammonia and rayon departments, while also creating new capabilities.[53] In May 1940, textile mills began shipping one of the iconic consumer products of mid-century – nylon stockings.[54]

During this same period, Du Pont continued to diversify through acquisition, buying up lucite, polyvinyl acetate, and the patents for titanium pigments, which the

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[52] Hounshell and Smith (1988, pp. 236-237); Mueller (1962, pp. 334-337).

[53] Hounshell and Smith (1988, p. 258).

[54] It is, wrote Schumpeter, "the cheap cloth, the cheap cotton and rayon fabric … that are the typical achievements of capitalist production, and not as a rule improvements that would mean much to the rich man. Queen Elizabeth owned silk stockings. The capitalist achievement does not typically consist in providing more silk stockings for queens but in bringing them within the reach of factory girls in return for steadily decreasing amounts of effort" (Schumpeter 1950, p. 67). Writing before 1942, he probably had not yet even heard of nylon.

company subsequently improved.[55] In 1943, a Du Pont researcher working with tetrafluoroethylene as a refrigerant accidentally discovered Teflon, which the company had little difficulty producing and marketing.

Oil was another industry in which research in scientific chemistry would ultimately become important. In 1924, university research sponsored by Jersey Standard dramatically reduced the costs of tetraethyl lead, the gasoline additive that had been invented by Kettering's lab at GM and was being produced more expensively by Du Pont.[56] Yet the major oil companies were far slower than Du Pont in establishing central research laboratories. After World War I, Jersey Standard president Walter Teagle believed that most important new technology of value to the company would come from external sources, and he approved what would be called the Development Department to scrounge for and then develop those external ideas rather than to engage, at least initially, in creative research.[57]

In the years leading up to the Depression, the biggest technical problem facing the oil industry was the efficient production of gasoline. In 1909, the value of petroleum products distributed in the United States was split roughly equally among kerosene, fuel

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[55] Mueller (1962).

[56] Gibb and Knowlton (1956, p. 541). Leaded gas was, of course, one of the great public-health disasters of the century. The toxicity of lead was well known at the time, but industrial researchers viewed it largely as an occupational-health problem – dozens of workers were killed or driven insane by exposure early on – not as an environmental problem. Yet many contemporaries in public health did speak out against lead. In 1925, the Surgeon General opened an investigation, and, despite wildly conflicting testimony, declared that there was no reason to ban the additive (Leslie 1983, p. 541). Jersey Standard became a co-owner (along with GM and Du Pont) of the Ethyl Gasoline Corporation to market the product, but initially Jersey itself refused to use the additive in its own gasoline (Gibb and Knowlton 1956, p. 543).

[57] Enos (1962, p. 104); Gibb and Knowlton (1956, p. 525).

oil, gasoline, and lubricant oils; in 1919, gasoline accounted for 55 per cent of the value, fuel oil 23 per cent, and kerosene and lubricating oils 11 per cent each.[58] The advance of electrification had eroded the market for kerosene as a source of illumination, and the automobile was hungry for gasoline. Already before the breakup in 1911, Standard of Indiana, the most technologically progressive unit of Standard Oil, had begun experimenting with thermal cracking, which used heat to break (or crack) the long molecules of crude oil to generate a greater yield of gasoline and other higher distillates. In 1913, under the direction of William M. Burton, a Johns-Hopkins-trained chemist who had been with the company since 1889, Indiana Standard developed and patented a thermal cracking process.[59] Other refiners, notably Jersey Standard and a technology startup called Universal Oil Products Company, began experimenting with thermal cracking, and many aspects of their developments overlapped with the principles of the Burton patents.[60] By 1919, after litigation and the threat of litigation, the industry was faced with a patent thicket not unlike those that had emerged in the contemporary aircraft and radio industries. Between 1919 and 1923, the application of new cracking technology virtually ceased.[61] In 1923, however, the major players negotiated a cross-licensing agreement that amounted to a patent pool – the "patent club."

As it increased the efficiency of gasoline production, the new technology also increased the scale of production; in the early twenties, a state-of-the art refinery came at

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[58] Williamson *et al*. (1963, p. 203).

[59] Enos (1962, chapter 1); Giddens (1955, p. 152).

[60] Enos (1962); Williamson *et al*. (1963, pp. 375-389). Universal Oil Products was founded by meatpacker J. Ogden Armour, who believed that refining should emulate the continuous-process (rather than batch) approach to production meatpacking had pioneered.

[61] Enos (1962, p. 118); Gibb and Knowlton (1956, pp. 554-555).

ten times the cost of a simple Burton still. This put pressure on the large number of small refiners who together produced a fifth of the industry's output. These small refiners vented their anger in Washington, where in 1923 Senator Robert M. La Follette had convened a Senate subcommittee to investigate "the High Cost of Gasoline and other Petroleum Products."[62] With the Teapot Dome scandal unfolding in parallel, the Coolidge administration quickly filed an antitrust suit against the firms in the patent pool, charging violation of both Section 1 and Section 2 of the Sherman Act.[63] The newly appointed William J. Donovan was made chief prosecutor. The defendants protested that a patent case should not be litigated under an antitrust statute, but a federal district court in Illinois handed the matter over to a Master in Chancery for adjudication. The Master found for the defendants and ordered the charges dismissed. The government appealed, and, in a 2-1 decision, an appellate court reversed the Master on many counts and ordered the patent pool dissolved. Finally, in 1931, Louis D. Brandeis delivered a unanimous Supreme Court decision reversing the appeals verdict.[64] Patent sharing and pooling in refining would have the sanction of the high court.

During the 1920s, Eugène Houdry became obsessed with producing higher-quality motor fuel.[65] A French engineer and industrialist – as well as an automotive enthusiast – Houdry began work on a process to crack crude oil using chemical catalysis rather than just heat, drawing on contemporary European attempts to extract oil from coal. By 1929,

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[62] U. S. Senate (1923).

[63] Gibb and Knowlton (1956, pp. 555-559); Giddens (1955, pp. 266-280); Williamson *et al*. (1963, pp. 389-391).

[64] *Standard Oil Co. (Indiana) v. United States*, 283 U. S. 162 (1931). Harlan Fiske Stone – who as Attorney General had initiated the case – recused himself.

[65] Enos (1962, chapter 4).

he had spent much of the family wealth on the project, with little to show for it; and after 1929, European firms (and the French government) showed no interest. So Houdry turned to the U. S., where the Vacuum Corporation began supporting the research, relocating it to New Jersey. But as the Depression deepened, Vacuum started cutting back; and when the company merged with Standard Oil of New York in 1931 to form Socony-Vacuum (eventually Mobil), Houdry's research was in jeopardy. He looked about frantically for new sources of support, and within a couple of years had caught the attention of the small, entrepreneurial, and privately held Sun Oil Company. With the often hands-on help of the owning Pew family, Houdry was finally able to get a profitable process up and running. By the end of the decade, a number of Houdry plants were in operation around the country, and catalytic cracking had emerged as clearly the future of refining. Because the process yielded gasoline of high octane – just as Houdry had always intended – all American Houdry plants were dedicated to aviation fuel during World War II, and 90 per cent of U. S. aviation fuel came from those plants.

But the oil industry's biggest problem in this era was not technological. It was a problem of collective action and political economy. Uniquely in the world, American law applied the rule of capture to oil production.[66] This means that one comes to own oil only by removing it from the ground; one cannot stake a claim to an entire pool of oil beneath the surface. Thus oil production was subject to a tragedy of the commons, perfectly analogous to the one in the international fisheries, which also operate on the rule of capture (by default because of the mobility of fish and the absence of enforceable international

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[66] Adelman (1972, p. 43).

law). Just as every fisher wants to catch as many fish as possible as quickly as possible, every producer who has drilled into an underground oil field wants to suck up as much of the collective oil as possible as quickly as possible. In oil, the inefficient dissipation of rents occurs because pumping the fluid out of the ground at too high a rate means that, because of the dynamics of sub-surface pressure, the pool will ultimately yield less, sometimes considerably less, leaving under the ground much valuable oil that can then be removed only at much higher cost. This problem, which was clearly understood at least by World War I, could have been solved by collective action – by a single producer owning an entire pool or by *unitization*, under which one owner operates the entire field but compensates the other owners according to a formula. Both of these alternatives create the incentive to try to maximize the net present value of the oil in the ground and to pump at a slower, more nearly optimal rate. Some economist have speculated that eventually producers would have recognized that unitization was in their collective interest.[67] But, because of the uncertainty surrounding the value and the geological characteristics of fields, the transaction costs of writing unitization contracts were extremely high.[68]

Thus in American oil fields in the early century, it was every man for himself, especially among the thousands of small drillers who hoped to strike it rich. Indeed, the only unitized field in the U. S. in this period was Teapot Dome, which Interior Secretary Albert Fall had leased in a block to Mammoth Oil.[69] Despite the fact that this form of leasing was the key to oil conservation, the leases were opposed by conservationist groups,

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[67] Adelman (1972, p. 44).

[68] Libecap and Wiggins (1984, p. 90).

[69] Libecap (1984). One ironic outcome of the Teapot Dome scandal was that all federal leases after 1930 would require unitization.

including the Yale School of Forestry, as well as by the small drillers who were shut out of the field. Along with Interior's rival Department of Agriculture, these groups fomented the hearings that led to the revelation of Fall's self-enrichment. In another symbolic response to the scandal, in 1924 the Coolidge administration created the Federal Oil Conservation Board, on which sat the Secretaries of the Interior, Commerce, War, and Navy Departments, along with industry representatives. The organization had no actual power to implement unitization but concentrated instead on forecasting demand to assist state bodies that were trying to regulate crude-oil production. In this respect, the Board foreshadowed the form federal intervention would soon take.

In the years before the Depression, politicians, journalists, and the American in the street fretted that the country might be running out of oil.[70] To oil producers, the experience was quite the reverse: as new fields were continually being discovered, the producers, not unlike America's farmers, were worried about "overproduction" and falling prices. The oilmen's worst fears came to pass in the calamitous year of 1930. A 70-year-old wildcatter named Columbus Marion Joiner elicited the first gusher from what would prove to be the humungous East Texas oil field, more than ten times larger than any previously known field in the U. S. The resulting supply shock, combined with the ongoing monetary deflation, sent the price of oil into freefall. In 1926, standard-grade crude had sold for $2.29 a barrel; by 1933, the price was 10 cents.[71] When in 1931 the Texas Railroad Commission, which had long been charged with regulating the literal physical waste of oil,

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[70] Ise (1926, pp. 402-422). In 1920, the director of the U. S. Bureau of Mines predicted that oil would run out in 18 to 20 years.

[71] Libecap (1989, p. 835).

attempted to place limits on production in the new field and to prorate the reduction among wells, a federal district court ruled that the Commission had exceeded its statutory authority and was merely attempting to create a price cartel.[72] Claiming that East Texas was on the brink of violence, oilmen then persuaded Texas governor Ross Sterling to declare martial law, which he did in August, sending in 1,300 troops from the Fifty-sixth Cavalry Brigade of the Texas National Guard to enforce prorationing.[73] In spite of the military presence, "hot oil" – oil produced in excess of prorationing quotas – continued to flow from East Texas wells. By 1933, the federal courts had reversed themselves on the legality of prorationing; but as of March of that year, East Texas was producing a million barrels a day, 600,000 over the quota set by the Railroad Commission.[74]

It was the NRA to the rescue.[75] The oil code put in place in September 1933 gave the federal government authority over prorationing, and it made Interior Secretary Ickes the oil czar. Crucially, the code made illegal any interstate shipments of hot oil, which effectively enforced state prorationing. Once again, Congress responded to the demise of NIRA in 1935 by crafting a legislative replacement targeted at a specific industry. The Connally Hot Oil Act reinstated the prohibition against interstate shipment of above-quota oil, and it created a Federal Petroleum Board to administer prorationing.

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[72] *MacMillan v. Railroad Commission of Texas*, 51 F.2d 400 (W.D. Tex. 1931).

[73] Olien and Olien (2002, p. 186).

[74] Libecap (1989, p. 837).

[75] Nash (1968, pp. 128-152).

Thus, between 1933 and 1972, the production stage of the oil industry in the U. S. would be a government-run cartel.[76] As would often be the case in other industries, the regulatory apparatus in oil worked to keep the nominal (not the real) price relatively constant over the years. Prorationing was not unitization; the very smallest wells were exempt completely from prorationing, and because quotas operated on a per-well basis, nothing stopped drillers from sinking new wells. But limiting output did at least move in the direction of correcting the externality problem in extraction. Because East Texas was so large and the oil so close to the surface, production costs there were extremely low, which threatened the thousands of small producers dispersed throughout the midcontinent and the many local businesses that supplied them. With the voting power of the scattered oil communities firmly in mind, state prorationing boards worked diligently to allocate oil quotas to small high-cost producers and away from large low-cost producers. As a result, for four decades in the middle of the century, the United States produced its oil in the costliest way possible.

Steel, America’s other mammoth nineteenth-century industry, was even slower than oil to adopt the central research lab. Andrew Carnegie had hired a chemist; but in the late nineteenth and early twentieth centuries, innovation in steel was driven mostly by the users of the product, not by the industry itself.[77] As the Depression began, United States Steel continued to dominate the industry. In 1930, it had assets of $2.4 billion, more than the next six largest competitors combined and more than three times the company’s nearest

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[76] Libecap (1989).

[77] Knoedler (1993).

competitor, Bethlehem Steel.[78] Yet in the first three decades of the century, U. S. Steel's share of the market had collapsed from something like two-thirds to more like one-third.[79] The relaxed stewardship of Judge Gary had allowed the company's smaller, more aggressive competitors to steal a march on the lumbering giant. This was nowhere more evident than in the domain of innovation.

The central technical problem of the 1920s was to improve the quality and efficiency of rolled steel strip, especially the wide strip increasingly in demand by the automobile industry, which was moving rapidly to the closed-body car. The technology of rolling had remained essentially unchanged since the nineteenth century: it was a labor-intensive batch process in which standardized quality was difficult to achieve. By the 1920s, however, the advent of small electric motors suggested the possibility of mechanizing the process. In 1921, John Butler Tytus began leading a systematic effort to develop technology for continuous rolling of sheet steel at the Ashland, Kentucky plant of the American Rolling Mill Company (later Armco), a small, closely held firm traded on the Cincinnati exchange.[80] By January 1924, the plant had rolled its first sheet, and by 1926, Tytus had a patent on the system. Harry M. Naugle and Arthur J. Townsend were thinking along similar lines, and in 1926 their firm, Columbia Steel, essentially a startup funded by Mellon venture capital, had a superior mill in operation at a former train-wheel plant in Butler, Pennsylvania.[81] Unlike the Armco project, which took place largely in

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[78] Warren (2001, p. 124).

[79] McCraw (1989).

[80] Hogan (1971, pp. 847-856).

[81] This short-lived Columbia Steel Company is not to be confused with the West-Coast-based Columbia Steel Company acquired by U. S. Steel in 1929 (Hogan 1971, p. 894).

secret with intellectual property in mind, the Columbia development involved the visible cooperation of both suppliers and customers, an example of what is nowadays called "open" innovation.[82] In March 1927, the Butler plant was rolling 16,000 tons of sheets a month. Seeing the threat to its own technology, Armco quickly acquired Columbia and consolidated the patents, creating what would prove to be the dominant design in mechanized steel rolling for decades. In less than ten years, more than 70 per cent of cold rolling was produced by the continuous process, a rate of diffusion of new steel-making technology surpassed only by the Bessemer converter in the nineteenth century.[83] By 1930, Armco was the sixth-largest steel company in the country.

As it produces a durable product virtually by definition, steel was hit hard by the Depression. An industry that had been running at almost full capacity in 1929 essentially shut down in December 1932, when average capacity use reached 15 per cent.[84] The NRA steel code offered temporary respite, even though, unlike those of other industries, it was written in terms of price stability not quotas; there would be no special legislation for steel after 1935. Although the steel industry responded to the Depression by closing inefficient plants, the productivity effects of this attempt at shaking out were probably lower than in automobiles and radios. Because of tight technical complementarities between stages of production – including the need to feed molten iron directly from a smelter into a steel

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[82] Aylen (2010).

[83] Gold *et al*. (1970).

[84] Baker (1989).

converter – firms were on the whole less flexible in reallocating work to superior facilities.[85]

The biggest companies, like U. S. Steel and Bethlehem, found themselves seriously overinvested in “heavy” products like rails and girders, the demand for which had declined by two-thirds, instead of “light” products like rolled sheet steel for cars and canned goods, the demand for which had declined far less and would recover far more quickly.[86] In 1932, U. S. Steel lost $71 million and Bethlehem lost $19.4 million; by contrast, Armco lost only half a million during the entire Depression, and National Steel, also a producer of light products, actually turned a profit of $26 million between 1931 and 1935. Over the course of the Depression, Bethlehem worked to lower the share of heavy products in its output from 78 per cent to 47 per cent, though by 1938 only 23 per cent of its capacity was in sheet, strip, or tinplate. The company came to regret its backward integration into minerals, as those could be had at distressed prices on markets during the downturn, although it benefited from its high rate of utilization of scrap, which could also be had cheaply. At the same time, it increasingly integrated forward during the Depression to gain control of distribution and even retail outlets, notably for the supply of pipes and other oil-production equipment. Bethlehem emerged from the Depression a more diversified steel company than it had been in the 1920s. In 1936, the original New Jersey corporation was merged into a new Delaware corporation along with two subsidiaries; in 1938, Bethlehem Shipbuilding Corporation was merged into the Delaware corporation as well.[87]

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[85] Bertin *et al*. (1996).

[86] Warren (2008, pp. 132-143).

[87] Hogan (1971, pp. 1216).

Shortly before his death in 1927, Judge Gary announced to the stockholders of U. S. Steel the formation of a central research laboratory in Kearny, New Jersey. It was, he told the stockholders, "the finest thing which we have done or attempted to do up to date."[88] Yet in 1927, the steel behemoth was not well organized to take advantage of those new research capabilities. Despite slow attempts at reform and integration since its founding, the company was still a super-sized gallimaufry of mismatched subsidiaries and divisions up and down the supply chain. Jack Morgan and the board were well aware that structural change was necessary, and they lined up activist executives to replace Gary, including Myron C. Taylor, head of the finance committee and eventually the new chairman and CEO.[89] Taylor demanded a study of corporate structure and instigated a $200 million plan for expansion and modernization – just as the Depression hit. Unsurprisingly, U. S. Steel responded slowly to the crisis, and was late in cutting prices and laying off workers. Even after hastily closing plants and consolidating holdings, the company still had 20 manufacturing subsidiaries and 143 works in 1932. The problem, suggested *Fortune* magazine helpfully, was that U. S. Steel "has been too big for too long."[90] Yet the Depression would ultimately provide the catalyst for major structural change. In addition to recommending further closings and consolidations, a consultant's report in 1935 called for the creation of a new Delaware corporation to sit between the holding company and the operating divisions. The new corporation would house the kind of large general staff that Alfred P. Sloan had put in place at General Motors. By the end of the Depression, under new president Edward R. Stettinius, Jr., a former GM executive and son of the man who

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[88] Mowery (1981, p. 113).

[89] Warren (2001, pp. 144-163).

[90] Warren (2001, p. 156).

had headed J. P. Morgan's Export Department during the war, the giant steel company would become – albeit briefly, as it would turn out – a multidivisional firm.[91]

Aluminum was not yet a major substitute for steel in this era. But World War I had provided many new uses. Critical parts of the Liberty Engine were cast from the metal, and in 1927 the *Spirit of St. Louis* crossed the Atlantic clad in aluminum. Far more than steel, aluminum was a science-based industry from the start, as it required knowledge of both chemistry and electricity to extract a usable metal from the mineral bauxite. In 1898, the Pittsburgh Reduction Company, which held the crucial patents, became the beneficiary of venture capital from Andrew Mellon. It transformed into the Aluminum Company of America, and continued to dominate aluminum production long after the original patents expired.[92] During the Depression, Alcoa reacted along familiar lines, deemphasizing cost-cutting research on refining and smelting in favor of research on new alloys for new products.[93] Many of these innovations were carried out in collaboration with users, in spheres as diverse as screws, beer barrels, buses, and, perhaps especially, aircraft, where the material's light weight offered clear advantages.

In 1929, the American automobile industry had produced almost 5.3 million motor vehicles; by 1933, that number was little more than 1.8 million.[94] In 1932, the industry as

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[91] Chandler (1962, p. 334). Although Stettinius had come from GM, his duties as an assistant to Sloan had been largely in the realm of public and government relations (Farber 2002, p. 152). Chandler credits the "highly rational business school graduate" Enders M. Vorhees with actually spearheading the change to the multidivisional structure at U. S. Steel.

[92] Nicholas (2019, p. 64).

[93] Graham and Pruitt (1990, p. 214)

[94] FTC (1939, p. 7). Motor vehicle registrations dropped only 10 per cent, meaning that Americans largely kept their old cars in service instead of buying new ones. Between 1930 and 1937, registrations increased by 20 per cent, most of that after 1933 (p. 17).

a whole lost $200 million.[95] Yet, in contrast to parts suppliers and dealers, who had their own separate codes, the large carmakers greeted the NRA with little enthusiasm.[96] Much to the consternation of General Johnson, Henry Ford flatly refused to sign the auto code, and there was absolutely nothing the NRA could do about it. Ford maintained the $7 day for unskilled workers for two years, but he cut labor costs in other ways, including by lowering the wages of skilled laborers. The company turned to subcontracting, in part to take advantage of lower wages among suppliers, which increased in number from 2,200 in 1929 to some 3,500 in 1930; the Rouge shut down facilities making brakes, rear axles, shock absorbers, and differential housings.[97] Although he made a show of insisting that suppliers pay high wages, even sometimes suggesting unionization, he drove the suppliers hard, and reports became rampant of speedups on the lines, both at Ford plants and among the suppliers. In 1933, workers struck at a Briggs body plant operating as an inside contractor at Highland Park, but the strikers won only token concessions. In the middle of 1931, half of Ford employees were on a three-day week.[98]

As he had in 1921, Ford was quick to cut prices when the Depression began, and, thanks in large part to the Model A, sales initially sagged only slightly. Ford had sold 1.7 million vehicles in 1929, and the number held at 1.3 million in 1930.[99] Ford gained market share as smaller competitors failed. But by 1931, Chevrolets and Plymouths appeared at competitive prices with advanced features. Henry Ford responded boldly by shutting down

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[95] FTC (1939, p. 13).

[96] Rae (1984, p. 80).

[97] Ford (1931, p. 74); Sward (1968, p. 220).

[98] "Ford to Maintain High Wages," *Barron's*, May 4, 1931, p. 26.

[99] FTC (1939, p. 653).

the Model A in late 1931 in favor of a new model with the option of a V-8 engine.[100] Largely because of Ford's willingness to rely on outside suppliers, the changeover to the V-8 was far briefer and less painful than the changeover to the Model A had been, despite the need to replace half the machine tools in the engine plant.[101] But the shutdown, combined with the competition from GM and Chrysler, sent Ford sales tumbling to little more than 600,000 in 1931 and fewer than 330,000 in 1932. In a brilliant act of innovation, the aging and increasingly isolated Ford demanded that the block for the V-8 be cast in a single piece.[102] The casting process was successful, but the engine initially performed poorly, as customers complained that it burned a quart of oil every 100 miles; and the superior economies of scale Ford imagined never materialized.[103]

Even though sales would reach one million again in 1935, the Depression was a period of relative decline for Ford. Many have understood this as a failure of research and development. "Being an engineer of the old school," wrote *Barron's* in 1932, "Ford proceeds by the empirical method. He builds, tries and approves or rejects projects without due regard for theory or science."[104] Although it had labs scattered around its plants, the company had no central R&D unit, and it even lacked a proving ground and basic testing facilities. To Nevins and Hill, accomplishments like casting the new V-8, "while more

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[100] This model became a favorite of hot-rodders in the 1950s and 1960s, immortalized by the Beach Boys as the *Little Deuce Coupe* – "deuce" referring to the 1932 model year. My father owned one of these in the late 1940s, having won it, he claimed, in a game of craps. (He always called it a Model B, but the B was the four-cylinder version; the V-8 was the Model 18.) Family lore has it that he would tour around with my uncle in the passenger seat and my mother and my aunt consigned to the rumble seat.

[101] Abernathy (1978, p. 105); Hounshell (1984, p. 300).

[102] Nevins and Hill (1957, p. 594). This was as against bolting to the crankcase two separate castings of four pistons each.

[103] O'Brien (1989a, p. 86).

[104] "Ford to Make Eight and Four," *Barron's*, January 11, 1932, p. 24.

astonishing for being wrought without adequate research facilities, merely emphasized the need for them."[105] It didn't help, of course, that the autocrat vetoed many of the innovations, including hydraulic brakes, longitudinal springs, and six-cylinder engines, that his underlings were proposing and his competitors were adopting.

If Ford's star was in relative decline, Chrysler's was very much on the rise. The symbol of Walter Chrysler's audacity, the magnificent Chrysler building in Manhattan, opened to commercial success in early 1930. Between 1929 and 1930, sales of Plymouth did fall 25 per cent.[106] But Chrysler lowered the price by $100, and in 1931 Plymouth was selling some 94,000 units, more than it had sold before the crash. In 1932, it sold almost 118,000. These numbers were small compared to those of Ford and Chevrolet; but unlike those of Ford and Chevrolet, they were moving in the right direction.

"I never cut one single penny from the budget of our research department," Chrysler bragged.[107] With a staff of 300 housed in its own five-story building in Highland Park, the company's research efforts were far more in the nature of development and testing than of basic research.[108] Two months before Ford introduced the V-8, Chrysler brought out a new six-cylinder car, the result of a $9 million investment program in the teeth of the Depression.[109] Although its price was competitive with Chevrolet and not much higher than Ford, the Plymouth 6 came loaded with advanced features, including hydraulic brakes,

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[105] Nevins and Hill (1962, pp. 59-60).

[106] FTC (1939, pp. 27, 536, 602, 653); Kennedy (1941, p. 235).

[107] Chrysler (1950, p. 200).

[108] "There Are No Automobiles," *Fortune*, vol. 2, issue 4, October 1930, pp. 73-77.

[109] Schwartz (2000, p. 88).

an all-steel body, a rigid x-frame chassis, and a system of rubber mountings to dampen engine vibration. Perhaps most significantly, Chrysler turned the new car into a genuine modular platform: customers could order from a menu of options including color and upholstery, and their choices would be transmitted to the assembly line to customize each car. "Timing is so perfect," marveled *Fortune* magazine, "that the specific car ordered by the specific customer comes together as rapidly and smoothly as though the 1,800 cars produced daily at the Plymouth plant were all identical instead of varied."[110]

During Chrysler's push into the low-price field, the company relied more heavily on vertical integration, especially the facilities made available by the acquisition of Dodge. Yet Chrysler remained far less vertically integrated than its competitors; and it was in large part this shallow vertical integration and reliance on innovative suppliers that underpinned the company's strategy of flexible product innovation.[111] In 1933, Plymouth sold more than 250,000 units; in 1934, more than 300,000.[112] By 1937, the Chrysler Corporation as a whole had edged out Ford as the number two carmaker in the country, selling more than a million units.

At General Motors, the Depression required a dramatic if temporary retreat from Alfred P. Sloan's strategy of product diversification and from the multi-divisional structure. A car for every purse and purpose made sense as incomes were rising; but as incomes (and confidence about future income) declined, sales of income-elastic mid-price vehicles fell faster than those of low-end cars. More integrated than Chrysler, GM had to

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[110] "Chrysler," *Fortune*, vol. 12, issue 2, August 1935, p. 114.

[111] Abernathy (1978, p. 37); Schwartz (2000, p. 90).

[112] Curcio (2000, p. 501); FTC (1939, pp. 27 and 602).

amortize its fixed costs over fewer units. In 1932, the Operations Committee decided to consolidate the manufacturing of Pontiac with that of Chevrolet (under William Knudsen) and the manufacturing of Oldsmobile with that of Buick.[113] Sales of Buick, Oldsmobile, and Pontiac were assigned to a single entity called B. O. P., and dealers were made to sell more than one marque. Significantly, the retrenchment destroyed much of the "decoupling" that had existed, in principle if not always in practice, between the divisions and the central headquarters: the systemic changes needed to effect drastic production economies required central control.[114]

Already in 1924, GM had established the industry's first dedicated proving ground.[115] In 1925, Charles Kettering's laboratory was relocated from Dayton to Detroit. By the time the lab moved into its new eleven-story building in 1929, it boasted a staff of 400, and by the end of the 1930s it would command a budget of $2 million a year.[116] In principle, 40 per cent of the lab's activities involved consulting on routine technical matters with the divisions; another 40 per cent was directed to advanced engineering; and the remaining 20 per cent focused on fundamental research, including topics like infrared spectroscopy and the molecular composition of fuels. The GM central research lab was responsible for the first mass-produced automatic transmission, the Hydra-Matic, in 1939.[117] Yet the lab remained a one-man show in many ways, and Kettering had free rein for his ideas, which often veered outside the automotive. In the 1920s, he had improved

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[113] Sloan (1964, p. 177).

[114] Kuhn (1986, p. 151).

[115] Sloan (1964, p. 253).

[116] Leslie (1983, p. 184).

[117] Jewkes, Sawers, and Stillerman (1969, p. 231).

the compression refrigerator for GM's Frigidaire division, leading to a joint venture with Du Pont to produce Freon.[118] By the 1930s, Kettering's attention had turned in a direction that would yield another avenue of diversification: the diesel engine.

In this era, railway locomotives were almost all driven by steam engines, and they were manufactured by only three firms, the American Locomotive Company (or Alco) and the Baldwin Locomotive Works, with 40 per cent of the market each, and the Lima Locomotive Works, trailing with 20 per cent.[119] By powering a dynamo to drive the kind of electric-traction systems that General Electric and Westinghouse had long been making for street trams, the diesel engine offered a potential alternative to steam. Alco had a diesel locomotive in service for specialized switching uses as early as 1924. But the four-stroke engines of the time were heavy and inefficient. Kettering was sure he could do better. He began developing a light and powerful two-stroke version, initially with marine uses (notably submarines) in mind. He even fitted out his own yacht with one, the better to tinker in the engine room while on vacation. But when Ralph Budd of the Burlington Railroad saw the experimental two-stroke in operation at the 1933 Chicago World's Fair, he insisted that it power a new streamlined passenger train he was having built – the Pioneer Zephyr, which would make a record-setting dawn-to-dusk run from Denver to Chicago on May 26, 1934.[120] Kettering did not have to work hard to persuade Sloan to diversify into locomotives. GM had already purchased two failing firms, the Electro-Motive Company, which made gasoline-electric railroad cars, and the Winton Engine Company, which made

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[118] Leslie (1983, pp. 218-226).

[119] General Motors Corporation (1975); Leslie (1983, pp. 229-275); Marx (1976).

[120] Leslie (1983, p. 268). An alternative account claims that it was H. L. Hamilton, head of GM's Electro-Motive Division, who brought the engine to Budd's attention (Overton 1965, p. 394).

diesel engines; these became GM's locomotive division. A new manufacturing plant went up in Illinois in 1935. After World War II, the GM diesel locomotive would supplant steam even in long-haul freight uses.

After it received the authority to set railroad rates in 1920, the Interstate Commerce Commission had evolved a system of keeping rates relatively constant and permitting a steady return of about 5.5 per cent.[121] Railroad profitability increased relative to the era before World War I and its variance declined; but capital investment continued its slow downward trend. The net stock of locomotives, freight cars, and passengers cars sank slowly over the decade of the twenties; so did employment. Always sensitive to the business cycle, the roads were hammered by the Depression. Freight tonnage plummeted from 1.4 billion in 1929 to 679 million in 1932. Passenger revenue had already receded by a third between 1920 and 1929 under pressure from automobiles and buses; between 1929 and 1933, passenger revenue fell again by almost two thirds in nominal terms.

America's large automobile firms, all controlled by founders or dominant blockholders, were financed mostly with equity, held relatively little debt, and had stored up considerable retained earnings to tide them over the worst years of the Depressions.[122] In stark contrast, America's railroads were typically owned diffusely or by holding companies, were financed importantly by bonds of maturity as high as 50 years, and

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[121] Field (2012, pp. 300-311); Hawley (1966, p. 229); Hoogenboom and Hoogenboom (1976, pp. 119-121); O'Brien (1989b).

[122] Chrysler was, of course, the exception, and it began the Depression indebted from its purchase of Dodge. But the company's countercyclical success in the product market allowed it to retire all of its debt by 1935 (Chrysler and Sparkes 1950, p. 201).

retained almost no cash.[123] Thus when revenues plunged in the Depression, the railroads were faced with fixed interest charges that were rising steadily in real terms. As Alexander Field puts it, "railroads were the poster child for Irving Fisher's debt-deflation thesis."[124] But there would be a silver lining: the railroads, Field believes, are an excellent example of how adversity spurred productivity growth during the Depression.

The railroads's initial response to the crisis was not to increase productivity; rather the opposite. Unable to borrow from the collapsing banking system, the roads diverted cash from maintenance, especially maintenance of way.[125] In effect, the railroads borrowed against their own future. This led to costly storage of machines and materials and the deterioration of the human capital of maintenance workers. Yet by the end of the Depression, Field shows, railroads were carrying more passengers and freight by value with fewer cars in less time, which suggests improvements in rail cars and in speed. Most of this effect occurred after 1939, when the economy was already gearing up for World War II.

Clearly, some roads did respond to the downturn by innovating. Prominently among these was the Burlington, which in this era was still controlled by the Great Northern and the Northern Pacific, which jointly owned more than 98 per cent of its stock. A veteran of the Panama Canal, Ralph Budd had risen through the ranks at the Great Northern as a top lieutenant to James J. Hill, ultimately becoming president in 1919, three years after

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[123] Schiffman (2003).

[124] Field (2012, p. 300).

[125] Schiffman (2003, p. 806).

Hill's death.[126] When he took charge of the Burlington in early 1932, Budd moved forward with the program of diesel-electric passenger trains. He also persuaded a feeder line to build an important short-cut, and he closed down some unprofitable routes, over the initial objections of the ICC. The Burlington avoided bankruptcy. Many others were not so fortunate. By 1935, some 30 per cent of U. S. railway mileage was in receivership.[127] The Reconstruction Finance Corporation moved quickly to help railroads avoid bankruptcy by lending them funds to cover their fixed charges. There is evidence, however, that those firms that actually entered bankruptcy fared better in the long run than those that borrowed from the RFC.[128] An RFC loan postponed the reckoning; but an appointed receiver had authority to make the kinds of sweeping changes that were necessary to regain profitability. For its part, the Burlington refused to borrow from the RFC.[129]

Whereas automobile makers responded to deflation by cutting prices, the ICC made sure to keep rail rates constant in nominal terms – which meant that rates were rising in real terms.[130] The commission even permitted an emergency rate increase. Under the leadership of Progressive commissioner Joseph Eastman, the ICC pushed through the Emergency Railroad Transportation Act of 1933 to create what was intended to be an NRA for the railroads. Eastman became the Federal Coordinator of Transportation, empowered to implement measures to reduce waste, including the pooling of facilities. Unsurprisingly, railroad managers stonewalled and threatened layoffs whenever Eastman proposed

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[126] Overton (1965, pp. 369-382).

[127] Schiffman (2003, p. 804).

[128] Mason and Schiffman (2004).

[129] Overton (1965, pp. 377).

[130] O'Brien (1989b).

anything, including a central research bureau. In the end, "he could accomplish little beyond the filing of learned reports and the introduction of some minor economies."[131] The Emergency Transportation Act expired without a fight in 1936.

Although they could not agree about how to coordinate among themselves, the railroads easily united against what all saw as a common external threat: the trucking industry. Initially, of course, railroads and trucking were highly complementary, and the railroads supported the growth of the trucking industry. Until well into the decade of the 1920s, decent roads did not extend beyond the city gates, so trucks provided last-mile shipping for the railroads in a much cheaper way than constructing dedicated rail spurs, and trucks couldn't compete with rails for intercity hauls.[132] But there had been a "good roads" movement since the early century, spurred initially by bicycle enthusiasts as much as by automobile drivers. By the early 1920s, Hoover's Commerce Department was holding conferences to standardize across states such crucial aspects of highway travel as the rules of the road and the meaning of traffic signals.[133] In 1926, the states finally coordinated on how they would implement a federal mandate to create a national highway system, and interstate road construction and improvement began in earnest – to be picked up in the next decade by the Public Works Administration and the Works Progress Administration. (Field believes that the supply-side benefits of this build-out of the road system were a further contribution to high productivity growth during the Depression.) At

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[131] Hawley (1966, p. 230).

[132] Field (2012, pp. 70-78).

[133] Vinsel (2019, p. 61).

the same time, technological advances continued to improve the capacity and durability of trucks.

Between 1925 and the end of the decade, the number of trucks on the road had increased by 50 per cent, and those trucks were increasingly carrying freight between cities.[134] Moreover, ICC ratemaking principles for railroads were designed to subsidize bulk shipments (notably of agricultural commodities) at the expense of high-value-added shipments like manufactured goods. This cross-subsidy allowed trucks to cream-skim. By 1933, the trucking industry was becoming a serious problem for the railroads. Of course, truckers also saw their revenues decline in the Depression: as economies of scale were non-existent, anyone who could scrape tougher enough for a used truck could enter the business unimpeded, leading to what the large truckers considered destructive cutthroat competition. So truckers welcomed their NRA code, although they strongly opposed ongoing attempts to place highway carriage under the authority of what they saw as a railroad-minded ICC. After the evaporation of NIRA, however, the railroads made sure that the Motor Carrier Act of 1935 did exactly that.

The Act gave the ICC the same powers over trucks as it had over railroads, including the setting of rates and the supervision of securities issues. Common carriers had to obtain certificates of public convenience and necessity, and contract carriers required licenses. (Agricultural shippers – surprise – were explicitly exempted.) Existing carriers were grandfathered in, but the requirements implied formidable barriers to new entry. The system tended to benefit larger trucking companies, which could spread the fixed costs of

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[134] Hawley (1966, pp. 231-234); Rothenberg (1994, pp. 42-44).

dealing with the ICC over a larger volume. As ICC control extended only to safety and hours regulation for private carriers, the Act also created an incentive for manufacturers and distributors to integrate vertically into trucking.[135] The industry quickly warmed to the new environment as rents began flowing both to the protected firms and to the unionized Teamsters who drove the trucks.[136] For 45 years, an industry with no detectable natural-monopoly characteristics would be regulated like a utility.

The federal government also worked hard during this period to create another competitor for the railroads, commercial aviation. After World War I, American manufacture of aircraft cratered: whereas the U. S. had produced 14,000 planes in 1918, it turned out a mere 263 in 1922.[137] Yet many entrepreneurs saw a potential in commercial air transport. One of these was William B. Stout, who solicited funds for a startup in his native Detroit in 1922.[138] Among the investors were Henry and Edsel Ford. So taken were the Fords with the idea of aviation that before long they had bought out Stout's company and begun manufacturing the first great commercial transport, the Ford Trimotor.[139] Ford Motor Company created an airport in Dearborn and developed its own air-freight service. Ultimately 199 Trimotors would be built, some remaining in service into the 1950s.

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[135] At about the same time he owned the Ford V-8, my father and a buddy got hold of a used truck and briefly tried their hand at the trucking business. No ICC permit was applied for. He continued to drive trucks of various sorts for most of his career, eventually at the end snagging a unionized position driving a tractor-trailer for a small secondary steel plant. But my father was a Steelworker not a Teamster: the truck belonged to the plant itself. This was really a mild instance of tapered integration, as most of the plant's shipping was handled by a (recently deregulated) contract carrier.

[136] Moore (1978).

[137] Rae (1968, p. 3).

[138] Nevins and Hill (1957, pp. 238-247).

[139] Immortalized (among many other places) in *Indiana Jones and the Temple of Doom* (1984).

Commerce secretary Herbert Hoover was also a believer in the future of commercial aviation, and he saw it as his responsibility to ensure that the U. S. had a strong and vibrant industry.[140] By 1925, the controversial general Billy Mitchell was also issuing a stinging critique of America's military preparedness in the air. At Hoover's instigation, the Coolidge Administration convened a President's Aircraft Board in 1926 to assess the state of American aviation. Howard E. Coffin was a prominent member, and the chair was Dwight W. Morrow, a Morgan partner, aeronautical enthusiast, and future father-in-law of Charles Lindbergh.[141] Following the Board's recommendations, Congress quickly enacted legislation calling for 1,600 new aircraft for the Army and 1,000 for the Navy by 1931.[142] It also passed the Air Commerce Act, conferring on the Commerce Department broad powers to promote commercial aviation, including building navigation and other facilities, devising traffic and safety rules, and licensing planes and pilots. Hoover enlisted the relevant trade associations and began calling conferences. By 1928, the department had licensed 2,000 planes and 3,000 pilots and had helped establish 207 municipal airports. In the view of William P. MacCracken, the assistant secretary for aeronautics, the department had also eliminated "competition from patched-up war surplus."[143]

As the American aviation industry developed, it began coalescing into several vertically integrated holdings companies structured not unlike General Motors under Billy

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[140] Hawley (1981, pp. 108-115).

[141] Also on the Board was Connecticut Senator Hiram Bingham, a Yale political scientist, aviator, and the amateur archaeologist who brought to modern world-wide attention the ancient Inca ruins of Machu Pichu. He is often alleged to have been an inspiration for the character Indiana Jones, though it is not known whether he ever flew a Ford Trimotor.

[142] Rae (1968, p. 23).

[143] Hawley (1981, p. 113).

Durant.[144] In 1925, an engineer called Frederick B. Rentschler was looking for venture capital for a spinoff to produce a new radial air-cooled engine he had devised with Navy contracts in mind. His brother, a director (and eventually chairman) of National City Bank, put him in touch with Colonel Edward A. Deeds, who was then chairman of the Niles-Bement-Pond Tool Company. In spite of his ill-treatment in the aviation hearings after World War I, Deeds provided Rentschler $250,000 and access to his company's Pratt & Whitney facilities on Capitol Avenue in Hartford, once the home of the Pope Electric Vehicle Company but now relegated to warehousing bales of shade-grown Connecticut River Valley cigar leaf. Rentschler incorporated the Pratt & Whitney Aircraft Company, its stock owned half by the Pratt & Whitney Tool Company (which was owned in turn by Niles-Bement-Pond) and half by Rentschler and a partner.[145] By the end of 1925, Rentschler's team had produced the Wasp engine, which quickly became a technological and commercial success. In 1928, with the help of the National City Company, Rentschler instigated the creation of a holding company called United Aircraft and Transportation Corporation to encompass not only Pratt & Whitney Aircraft but also an assortment of airframe makers including Boeing and Sikorsky, parts makers like Hamilton Standard, and several associated airlines.

A less-integrated holding company was North American Aviation. It brought together a variety of aviation properties, some of them owned by General Motors, which would end up with a 30 per cent share. One of the company's divisions manufacturer the other important trimotor transport of the era, under license from the Dutch designer

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[144] Freudenthal (1968, pp. 76-83); Rae (1968, pp. 28-29 and 39-48).

[145] Sullivan (2008, p. 6).

Anthony Fokker.[146] The group also featured a number of airlines, including Eastern Air Transport, Western Air Express, and Transcontinental Air Transport. The holding company's jewel in the crown was Curtiss-Wright – an ironic-sounding merger of the two warring patent litigators of the early industry, even though neither personage was actually connected to the enterprise any longer – which made an air-cooled engine competitive with the Wasp. As GM's role in North American increased, Curtiss-Wright spun off and became a major aviation company in its own right. The fourth major player was the Aviation Corporation (or AVCO), which had been set up by a group that included Sherman M. Fairchild, with funding from the Harrimans and Lehman Brothers. An inventor and entrepreneur, Fairchild had gone into aircraft manufacture because he couldn't buy on the market any planes suitable for the aerial-photography equipment he had developed. In addition to airframe and engine producers, AVCO owned American Airways. Major investors (including GM) held stock in more than one of these holding companies, and there was non-negligible overlap in their boards of directors. Charles F. Kettering was involved with at least three of them in one way or another.

Why did the aviation industry organize in this way during this era? As had been the case with Durant's GM and with contemporary utilities, the holding company form brought together a coherent portfolio of complementary assets, creating a low-transaction-cost investment vehicle for money that was bullish on the prospects of a sector as a whole, thereby providing smaller complementary businesses with access to capital. Beyond this,

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[146] Rae (1968, p. 15). In 1931, the crash of a TWA Fokker transport killed the famed Notre Dame football coach Knute Rockne, on his way to Hollywood to consult on a movie. The resulting adverse publicity is said to have helped motivate the developments in aircraft technology that led to the DC-3 and later mature airliners.

however, the group form of organization provided coordination benefits within a rapidly changing technological environment. An airplane is a complex-systems product; and, especially in this early period of systemic design change, close coordination could be crucial across stages of production that relied on very different knowledge bases. For example, the military rejected the controllable-pitch propeller as not worth the cost. But designer Frank Caldwell understood that the invention would be valuable only if airframes themselves were suitably re-engineered to take advantage. When he moved from a military lab to Hamilton Standard, he was able to work with Boeing to incorporate controllable-pitch propellers into the design of the company's future planes.[147] Also, like rail, aviation was a high-fixed-cost industry, and a holding company could act as an internal capital market to fund up-front development costs and to buffer what were typically large and lumpy sales.

It goes without saying that American aviation between the wars was a beneficiary of what we now call industrial policy. For the most part, that took a form that would remain typical in the U. S.: military procurement. As was universal around the world, the government was the dominant buyer of aircraft. The Army also engaged in its own aeronautical research, especially in its facility at McCook Field (now Wright-Patterson Air Force Base).[148] The research facilities of the National Advisory Committee for Aeronautics also made important contributions. Consciously choosing to focus its limited resources on aerodynamics, the organization developed, among other things, the famous NACA cowl, a streamlined housing to incorporate engines into the airframe. Perhaps

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[147] Rae (1968, p. 63).

[148] Phillips (1971, pp. 116-121).

because its successor agency NASA is not perceived as a military organization, many have understood NACA to have been an instrument of civilian industrial policy. In fact, it was focused centrally on military technology, even more so after Hoover's abortive attempt to commandeer it for the Commerce Department; much of NACA's research was classified.

During the interwar period, technological advance in aircraft came from a variety of sources: from the aircraft companies themselves, spurred by both military and commercial demand; from military research; from universities; from the airlines; and from Europe.[149] Although there were certainly spillovers to commercial aviation from the military, technology in this era flowed as often in the other direction as well.[150] The result was a revolution in aircraft design and performance, the apotheosis of which, in the commercial sector at least, was the Douglas DC-3 in 1936. By one appraisal "the most important innovation in the history of commercial aircraft up to that time," the DC-3 would become the dominant design for commercial airliners until the era of the jet engine.[151]

The only genuine civilian industrial policy toward aviation in this era came from Herbert Hoover. The U. S. Post Office had been relying on small existing aircraft, mostly war-surplus DH-4s, to deliver the mail. In 1925, the Kelly Airmail Act authorized the Post Office to contract with private carriers for airmail delivery. Hoover was dissatisfied with the system, which, he believed, charged rates that were too high. He also thought the system did little to encourage passenger transportation, and it involved too many

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[149] Rae (1968, p. 59).

[150] Phillips (1971, p. 119).

[151] Mowery and Rosenberg (1999, p. 62).

companies, flying routes that were too short.[152] When he became president, Hoover moved to remake air transportation. At his insistence, Congress passed the McNary-Watres Act in 1930, which changed the basis for computing airmail rates. It also effectively subsidized passenger transportation and the use of more-sophisticated aircraft, and it endowed the Postmaster General with near-dictatorial authority to reorganize the industry. Hoover instructed his Postmaster General, Walter Folger Brown, to call together the big carriers – in what became known as the "spoils conference" – to split the country into four east-west routes and a handful of north-south routes. Brown even demanded that North American merge together its Transcontinental Air Transport and Western Express airlines, along with a couple of smaller lines, into Transcontinental & Western Air (TWA). The idea was to develop a few financially strong long-distance carriers that would energize a market for bigger and more-comfortable passenger planes.[153] To this end, Brown let contracts not to the lowest bidder but to the lowest "responsible" bidder, the better to keep out what he considered wasteful competition from shoestring operators using war-surplus equipment.

Smaller operators became upset when they discovered that they had lost contracts despite having submitted substantially lower bids. After Franklin Roosevelt took office, word of this reached Senator Hugo Black, who launched well-publicized hearings. Although United Aircraft had been a reluctant participant in the spoils system – not having wanted to share the skies with its lesser rivals – the Black hearings focused the spotlight on United and on Rentschler personally. Roosevelt immediately canceled all the airmail contracts and assigned the Army Air Corps to deliver the mail. During a bitter winter, a

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[152] Hoover (1952, pp. 243-244).

[153] Mowery and Rosenberg (1982); Rae (1968, pp. 52-54).

dozen ill-trained and ill-equipped corpsmen died in the attempt. It was left to Roosevelt's Postmaster General, James Farley, to clean up the mess, which he did by reassigning the airmail contracts back to all the disgraced airlines, although at lower rates.

The associationalist scheme that Hoover and Brown had cooked up for aviation was, of course, very much in the spirit of the NRA and the early New Deal. (The airlines had not even bothered to put together a code by the time NIRA was off the books.) Hugo Black was thus flying very much against the *zeitgeist* (albeit against a Republican instantiation of the *zeitgeist*) when he sponsored what would become the Air Mail Act of 1934.[154] The Act capped rates and even personal salaries; forbade mergers and interlocking directorates; and assigned the ICC joint authority with the Post Office in supervising contracts. Most significantly, the Act vertically unbundled the aviation holding companies, spinning United Airlines off from United Aircraft, American Airlines off from AVCO, and Eastern Airlines and TWA off from North American. In keeping with Black's animus against United, the Act also split that company's manufacturing operations in two, creating a western company around Boeing in Washington and an eastern company (retaining the United Aircraft name) around Pratt & Whitney, Hamilton Standard, and Sikorsky in Connecticut.

Yet the *zeitgeist* could not be kept at bay for long. The administrative aspects of the 1934 Act were a disaster, and in 1938 Congress passed the Federal Aviation Act, creating a new independent agency, the Civil Aeronautics Board, to provide the airlines with the same kind of classic public-utility regulation enjoyed by other modes of

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[154] Hawley (1966, pp. 240-244).

transport.[155] For 40 years, the CAB would eliminate airfares as a margin of competition and would maintain all-but-impregnable barriers to entry in commercial air travel, requiring certificates of public convenience and necessity for all new routes. American, Eastern, TWA, and United, along with Juan Trippe's Pan American Airways, would have virtually exclusive control over U. S. trunk routes for more than a generation.

In the era before World War II, the electrical equipment and electronics industries rivalled chemicals in the creation of internal research and development capabilities. As befitted an organization that could trace it roots to Thomas Edison, General Electric was the first major American company to establish a formal central R&D lab.[156] Although Edison's Menlo Park operation had been run more like a twentieth-century corporate lab, including the use of scientific principles, than is generally credited, the Morgan-led merger with Thomson-Houston initially refocused GE's attention on consolidating the key technologies of the electrical revolution rather than on innovation. Before the turn of the century, the company hired the German-born physicist Charles Proteus Steinmetz in the Calculating Department of its huge Schenectady works devoted to electricity generation and transmission machinery. The brilliant Steinmetz was able to characterize the behavior of alternating current mathematically. He soon began pushing GE to create a genuine research-and-development lab. In 1900, Steinmetz enticed an MIT chemist named Willis R. Whitney to work three days a weeks in the carriage barn behind his personal residence on the banks of the Erie Canal. The next year, Steinmetz finally persuaded the company to make the lab official. In GE's annual report for 1901, vice president Edwin W. Rice

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[155] Dempsey (1979).

[156] Reich (1985); Wise (1985).

told stockholders that "it has been deemed wise during the past year to establish a laboratory to be devoted exclusively to original research. It is hoped by this means that many profitable fields may be discovered."[157]

Because General Electric encompassed a nexus of still relatively inchoate technologies at the core of electricity and electronics, it would indeed move into many profitable fields, a process of increasingly unrelated diversification that, for good or ill, would come to characterize the company throughout the century. As the research lab, and the company itself, worked to solve technological problems and overcome bottlenecks, the solutions they came up with frequently created new capabilities that pointed to subsidiary and sometimes clearly distinct industries.

As the electrochemical lab took shape with Whitney as its director, GE brought on board promising scientists like Irving Langmuir (who would win the Nobel Prize in physics in 1932) and William Coolidge. Once Langmuir got his hands on the De Forest audion tube, the science behind which De Forest himself had never understood, he was immediately able to improve it dramatically, leading to powerful tubes that could be used to improve broadcasting. Coolidge took the technology further up the frequency spectrum, creating an efficient high-voltage x-ray tube that gave the start to GE's medical-imaging business. Langmuir solved problems of heat transfer for GE's refrigerator division, which would become the avatar of the company's white-goods line of business. (GE had entered the refrigerator business late, taking advantage of the mistakes of earlier entrants in an industry that was exploding in size and undergoing a rapid shakeout of small firms.

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[157] *Tenth Annual Report of the General Electric Company*, January 31, 1902, p. 13.

Americans had bought only 75,000 refrigerators in 1925; by 1928 they were buying almost half a million; and by 1930 GE alone was selling a million units, less that GM's Frigidaire division but more than third-place Kelvinator.)[158] Other parts of the company had developed the steam turbine for electricity generation, creating capabilities that would enable GE's post-war foray into jet aircraft engines. Inspired by the polymer discoveries of Carothers at Du Pont, GE even began moving into plastics, drawing on company-wide knowledge of the properties of electrical insulators.[159]

For most of the pre-World War II period, some 20 per cent of GE's business emanated from Edison's famous invention, the incandescent light bulb.[160] Following the typical turn-of-the-century pattern, GE formed a cartel of lamp makers after Edison's basic patent expired. This included a market-sharing arrangement with Westinghouse. GE also engaged in resale price maintenance and other non-standard forms of contract, and it surreptitiously acquired control of one of its main competitors, the National Electric Lamp Company, which was the sole supplier of lamp bases in the country. The Taft administration filed an antitrust suit; but GE was pleased to give up all these arrangements in a consent decree that affirmed as immune to antitrust law its genuine source of market power, patents.[161] Bizarrely, the consent decree demanded that GE completely dissolve National and run that business under the GE name.[162] The decree also specifically barred

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[158] Rees (2013, pp. 147-152).

[159] Coe (2000).

[160] Bright (1949); Reich (1992).

[161] *U. S. v. General Electric Co. et al.* (1911), 1 D&J 267.

[162] Implying that the real sin was thought to be secretive ownership rather than market power. In fact, National was well-run company with its own research lab, and it almost certainly generated more value for GE as an independent subsidiary than as an internal division(Rogers 1980, pp. 97-98). GE continued to give its National division free rein for years after the consent decree.

the company from engaging in resale price maintenance. GE responded by setting up a consignment system to evade the ban, and it pushed the Justice Department into an antitrust suit to test the validity of the scheme.[163] In 1926, the Supreme Court resoundingly declared that "both the Westinghouse licensing agreements and the consignment system were legal mechanisms for General Electric to obtain the maximum revenue from its patents."[164]

GE's real problem in this period was technological. The basic Edison lamp had evolved little, and it remained dim, reddish, inefficient, and short lived. European competitors, backed by strong German science, were tinkering with alternative materials for the bulb's filament. In 1909, Coolidge developed and patented a process to make tungsten ductile enough to be formed into a filament, which yielded a new and brighter bulb that GE would market as the Edison Mazda lamp, named after the Zoroastrian god of light.[165] The company's attention turned to mass production, dramatically lowering prices to consumers over the next decades as it devised and improved manufacturing technology; labor productivity in lamp-making increased fourfold over the twenties. A 75-watt bulb that cost 75 cents in 1920 cost 20 cents in 1933 and 15 cents in 1938.[166] As GE came to dominate the lamp business, its products established national standards, including those for bulb sizes and types.

Because it consisted largely of durable goods, GE's overall business suffered in the Depression. The research lab, which had been spending some $2.6 million with a staff of

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[163] *U. S. v. General Electric Company* (1926), 272 U.S. 476.

[164] Rogers (1980, p. 113).

[165] Wise (1985, pp. 134-135).

[166] Bright (1949, p. 269). That's a decline by two-thirds in real terms, from roughly $9.60 of today's dollars in 1920 to $3.96 in 1933 to $2.73 in 1938. At the same time, the reliability of the bulb had improved.

some 250 scientists and engineers in 1929, saw its fortunes reduced to $1 million a year in the early thirties and its staff cut in half.[167] (The need to fire so many people drove the already unstable Willis Whitney into a nervous breakdown.)[168] But profits from light bulbs – a quintessential ephemeral product – helped tide the company over. In 1933, the heavy-equipment businesses lost $11 million, whereas the lamp division made a profit of $17.6 million.[169] GE maintained its prices for lamps during the worst years of the Depression, making up for lower sales by continuing to reduce costs. Sales of lamps turned up in 1933, and in 1935 the company slashed prices across the board. Like other large corporations, GE relied on retained earnings during the Great Depression and World War II, never turning to the financial system for funds. Indeed, in 1935 it paid off all its debt and preferred stock.[170]

GE's rival Westinghouse also had a long tradition of research driven by the need to solve engineering problems.[171] Before the turn of the century, Nicola Tesla worked for Westinghouse briefly and ineffectually after selling the company his patents; other Westinghouse researchers had greater success at introducing science and mathematics to the design of induction motors. In 1916, eight years after founder George Westinghouse had been forced out, the firm set up a formal R&D lab for basic research in a separate facility near the East Pittsburgh plant. The lab began hiring Ph.D. scientists, including the young Arthur Compton, a future Nobel laureate who would become one of the most

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[167] Wise (1985, p. 246).

[168] Hounshell (1996, p. 23).

[169] Reich (1992, p. 331).

[170] O'Sullivan (2006, p. 635).

[171] Kline and Lassman (2005).

significant figures in American science in the twentieth century. Yet, unlike its counterpart at GE, the Westinghouse lab failed to generate new lines of business diversification. In part, this reflected the tension between the engineering culture at Westinghouse and the scientific aspirations of the researchers. Arthur Compton grew frustrated trying to conduct his experiments on x-ray diffraction while at the same time being directed to work on the development of sodium-vapor lamps. He left for a brilliant academic career in 1919. More significantly, perhaps, Westinghouse's incentives to innovate, especially in incandescent lighting, had arguably been blunted by the 1911 consent decree, which accorded the company access to more than 200 GE lamp patents.[172] By 1920, as we saw, Westinghouse had begun to focus on the new technology of radio broadcasting. Although (unlike at GE) radio had originated outside of the research lab, it began to absorb most of the lab's energies after the company acquired the patents of inventor Howard Armstrong. The first era of fundamental research at Westinghouse was over.

Smaller and always more financially fragile than GE, Westinghouse – diffusely held since the ouster of the founder – was hit harder by the Depression than its rival. Even though its cash position was worse than that of GE, the company was nonetheless able to avoid the market for short-term debt before the recession of 1937.[173] As the economy improved in 1935, Westinghouse management decided to try to emulate the kind of "blockbuster" innovation coming out of places like GE and Du Pont, and reoriented the lab once again toward fundamental scientific research, including nuclear and solid-state

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[172] Reich (1992, p. 316).

[173] O'Sullivan (2006, p. 636).

physics and mass spectroscopy.[174] Yet Westinghouse would be only a junior collaborator in the breakthrough lighting product of the era, which would emerge from GE's lamp-development department rather than primarily from the Schenectady lab.[175] In 1938, General Electric and Westinghouse introduced fluorescent light.

Like GE and Westinghouse, AT&T evolved out of the work of inventors, not only Alexander Graham Bell but also his great rival Elisha Gray, whose Western Electric Company fell under control of the Bell interests in 1881. In the early years, technical matters were supervised by Thomas Watson, Bell's famous interlocutor, who was a trained scientist. Technical change was driven almost entirely by small outside inventors.[176] When he took charge of AT&T in 1907, Theodore Vail energized a more formal commitment to science and invention.[177] This was in large part because there were technological problems standing in the way of his goal of universal service, which, as we saw, meant not a phone in every home but a single unified telephone system under Bell control.

Vail's first problem was long-distance service.[178] Without cross-country communication, a nation-wide network would be impossible. But even using step-up transformers, a telephone signal would barely make it from New York to Chicago. In 1911, a special research branch within Western Electric began the hunt for some kind of active amplification – for a "repeater." After trying various mechanical approaches without

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[174] Kline and Lassman (2005, p. 637).

[175] Bright (1949, pp. 388-395).

[176] Reich (1985, p. 177).

[177] Galambos (1992).

[178] Hoddeson (1981).

success, the researchers caught wind of De Forest's audion, and in 1914 AT&T acquired the patent. By the end of that year, there were repeaters strategically placed across the country. In January 1915, AT&T conducted the first official transcontinental phone call with great ceremony. Alexander Graham Bell in New York uttered his iconic tagline: "Mr. Watson, come here, I want you." Speaking from the Panama-Pacific International Exposition in San Francisco, Watson laughed that it would now take him five days to get there. President Woodrow Wilson was also on the call from Washington, and a vacationing Vail was looped in from Jekyll Island. Improving the vacuum-tube-based repeater would occupy the attention of Western Electric research for the next decade and beyond.

As Vail's vision of a unified system took shape, AT&T found itself hooking together local operating companies with a bewildering assortment of idiosyncratic technologies. Standardization was thus another critical issue. This was a job for engineering not research, and in 1919 standardization came under the direction of Bancroft Gherardi, head of the operations and engineering department of Western Electric, which had been broken off from the research department that would soon become Bell Labs. Balancing collaboration and fiat, Gherardi operated as an in-house Herbert Hoover, calling conferences and assembling manuals of best practice. By 1929, "engineers in the Bell System had created standards for an astonishing variety of functions, including telephone plant design, underground cables, raw materials, manufacture, distribution, installation, inspection, and maintenance of new equipment, business and accounting methods, nontechnical supplies (such as office furniture, appliances, janitors' supplies, cutlery, and china), and provisions for safety, health, and even responses to sleet storms."[179]

In January 1925, under new president Walter S. Gifford – the statistician who had worked for Howard W. Coffin and the War Industries Board during World War I – AT&T spun off the research functions of Western Electric into a separate company, leaving behind the engineering and development functions. With some 3,000 employees, Bell Telephone Laboratories would be owned 50 per cent by AT&T and 50 per cent by Western Electric.[180] This completed the company's transformation into its mature mid-century form: two regulated arms, the local operating companies the Long Lines division, and two unregulated feet, Western Electric and Bell Labs.[181] The relationship between the regulated and unregulated parts of AT&T would be the fulcrum of conflict between the company and its regulators for much of the century.

Although the telephone had penetrated deep into American households, it remained enough of a luxury that, as the Depression descended, millions began to disconnect.[182] In 1931, the number of Bell phones in service fell by almost 300,000; in 1932 the number slid

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[179] Russell and Vinsel (2017, p. 126). As we will see, after Congress initiated an investigation of AT&T in 1935, the Federal Communications Commission found plenty to complain about. But it had only good words to say about the company's efforts in standardization. "The equipment and methods used in the Bell System have been standardized to a remarkable extent with resulting economies in manufacture of equipment and operation of telephone plant; flexibility in the interchange of equipment and trained personnel between different parts of the System; and a uniformly high quality of service" (U. S. Federal Communications Commission 1939, p. 584).

[180] American Telephone and Telegraph Company, *Annual Report of the Directors to the Stockholders for the Year Ending December 31, 1924*, pp. 18-19; Hoddeson (1981, p. 541). AT&T in turn owned 98 per cent of the stock of Western Electric.

[181] Temin and Galambos (1987, p. 13). The spinoff of Bell Labs was part of a larger restructuring in which AT&T sold off its international operations to ITT and, as we saw, divested itself of radio broadcasting.

[182] Adams and Butler (1999, p. 132); Brooks (1976, pp. 188-192).

by more than 1,650,000. Counting independents, one American phone in ten had disappeared. As in other regulated sectors, rates began to rise in real terms because nominal rates remained unchanged. In Wisconsin, David Lilienthal, the soon-to-be TVA administrator, was at the forefront of a movement among state regulatory agencies to eliminate red tape so that rates could be cut more quickly. AT&T began laying off workers – 32 per cent at both the local operating companies and Bell Labs and an astounding 78 per cent at Western Electric, whose equipment was no longer needed. The division lost $12.6 million in 1932 and $13.8 million in 1933. The transition from human operators to mechanical dialing was already underway before the Depression, and many of the layoffs at the regional companies were among operators, mostly female; at the same time, in Gifford's estimation, Western Electric might have shut down completely if not for work converting to the mechanical system. AT&T tried its best to spread the work around. Yet the company did not lower wages for those who remained employed. Nor – significantly – did the company reduce its annual dividend from the accustomed $9 a share even though earnings per share were significantly below that number until 1936. Many understood AT&T's policies as harming labor for the benefit of capital, but Gifford also earned much praise for maintaining "purchasing power."

Maintaining high dividends for AT&T's diffuse legion of stockholder was no doubt also motivated in part by the company's ongoing existential fear – amplified by the New Deal – that telephone would be nationalized into the postal system, as it had been in most other countries around the world.[183] Research was at the forefront of AT&T's strategy to

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[183] When he was an official of the Post Office Department, Daniel C. Roper, Roosevelt's commerce secretary, had drafted a report calling for telephone to be incorporated into the U. S. Post Office. By 1934, however, he was a supporter of regulation rather than nationalization (John 2010, p. 411).

avoid “postalization.” By slowly and steadily lowering costs and improving technology, the company could demonstrate its superiority over its state-owned counterparts in places like Britain and France, which was not necessarily a high bar to clear.

Despite the stringencies it imposed, the Depression was indeed a period of rapid advance at AT&T.[184] The company made improvements in areas such as radio telephony and switching; in 1936, it introduced coaxial cable. There is some evidence that, as has often been claimed, AT&T suppressed potentially disruptive innovations. This famously included magnetic-tape recording, which Bell Labs developed in 1934.[185] AT&T officials believed that users would fear having their secret conversations recorded, to such an extent that it would destroy telephony. At the same time, however, because Bell Labs was funded directly by a formula from the rate base, it did not have to drum up business from the operating divisions; and it thus became arguably the American corporate lab most dedicated to genuinely fundamental research. In 1927, Harold S. Black invented the negative-feedback amplifier, still widely in use, which would open up, among many other things, the possibility of high-fidelity sound reproduction. In 1937, Clinton J. Davisson won the Nobel Prize for his experiments on electron diffraction, the first of several that Bell scientists would earn. In that same year, Mervin J. Kelley, the director of research at the Labs, approached one of Davisson’s colleagues, a young physicist in the vacuum-tube department named William Shockley, with the challenging proposition that solid-state physics might one day yield a radically new approach to telephone switching. Although

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[184] Brooks (1976, pp. 202-203).

[185] Clark (1993).

Shockley’s research would be postponed by the war, it would ultimately lead to the most disruptive innovation of all.

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