Fission, Forking, and Fine Tuning

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March 2017

ABSTRACT

Perhaps because we live in the age of the Internet and social networks, everyone seems agreed that innovation is all about recombination. Although not fully dissenting from this consensus, and perhaps in the end affirming it in an important way, I want to draw attention to some apparently different mechanisms of innovation, both suggested by Adam Smith: *subdivision* (or *differentiation*) and *fine-tuning*. On the surface at least, these – especially the second – do not appear to be processes of recombination. I will attempt to elucidate what I mean by these concepts and try to think about how they fit together with recombination in a full Smithian account of innovation. Whether innovation proceeds from the top down or the bottom up depends crucially on the structure of complementary stages in the process of production. Especially if it takes place in a non-modular way, recombination may require unified decision rights, implying the vertical integration of complementary stages of production, in order to overcome the dynamic transaction costs of change. But the processes of subdivision and differentiation may also require changes in decision rights in order to overcome dynamic transaction costs. I illustrate these points with a case study of three generations of an American family of inventor-entrepreneurs in electricity and electronics.

Paper for the symposium on Innovation and Creative Production:
"Innovation from the Bottom-Up," December 2, 2016, New York University, and for the WINIR Symposium on the Legacy of Ludwig Lachmann, April 11-13, 2017, Johannesburg.

> In the first place, the view, widely held, of product variation as a monopolistic practice perpetrated by wily producers on an unsuspecting public, and incompatible with competition, is quite wrong. On the contrary, we have to learn to see it as forming part and parcel of the competitive market process and, often, an indispensable element of technical progress. Can anybody imagine how the aircraft, gramophones or typewriters of sixty years ago could have evolved into their present types without continuous product variation? Are the particular designs of goods we find at any point of time not the result of market processes?
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> -- Lachmann (1986, p. 16)

Perhaps because we live in the age of the Internet and social networks, or perhaps because we live in the age of recombinant DNA, everyone seems agreed that innovation is all about recombination. Unanimity on this point extends from growth theory (Weitzman 1998) to economic history (Mokyr 2002) to technology management (Fleming 2001). As author Matt Ridley put it in a much-viewed TED talk and elsewhere, innovation is about ideas having sex. Although not fully dissenting from this consensus, and perhaps in the end affirming it in an important way, I want here to draw attention to some apparently different mechanisms of innovation, both suggested by Adam Smith: *subdivision* (along with the related process of *differentiation*) and *fine-tuning*. On the surface at least, these – especially the second – do not appear to be processes of recombination. I will attempt to elucidate what I mean by these concepts and try to think about how they fit together with recombination in a full Smithian account of innovation.

Smith certainly understood the importance of recombination, of course, and he helps us understand why recombination is in a fundamental sense a "top down" rather than a "bottom up" mechanism. I will try to suggest that whether innovation proceeds from the top down or the bottom up depends crucially on the structure of complementary stages in the process of production.

Whether innovation occurs from the top down or the bottom up depends on the characteristics of the technology itself. But it also depends on institutions. I will argue that, in order to carry out innovation, entrepreneurs (who may or may not also be inventors) require appropriate *decision rights* in order to bring about the necessary changes. Especially if it takes place in a non-modular way, recombination may require unified decision rights, implying the vertical integration of complementary stages of production, in order to overcome the dynamic transaction costs of change. But the processes of subdivision and differentiation may *also* require changes in decision rights in order to overcome dynamic transaction costs.

I illustrate these points with a case study of three generations of an American family of inventor-entrepreneurs in electricity and electronics.

Adam Smith on innovation.

"The greatest improvement in the productive powers of labour, and the greater part of the skill, dexterity, and judgment with which it is any where directed, or applied, seem to have been the effects of the division of labour" (Smith 1976, I.i.1). These are the very first words of Book I of the *Wealth of Nations*. Contrary to the teachings of the mercantilist writers – Smith essentially coined that term – the wealth of nations consists in productivity, and the division of labor is the key to increasing productivity. Unlike Ricardo, Smith was after a theory of economic growth, not a theory of optimal trade. It is not that pre-existing differences in productivity make trade desirable; it is that trade makes changes in productivity possible, which generates economic growth. Trade is one way of increasing the extent of the market, and an increased extent of the market calls forth and supports a process of learning by doing.

How does it work? “This great increase of the quantity of work which, in consequence of the division of labour, the same number of people are capable of performing, is owing to three different circumstances; first to the increase of dexterity in every particular workman; secondly, to the saving of the time which is commonly lost in passing from one species of work to another; and lastly, to the invention of a great number of machines which facilitate and abridge labour, and enable one man to do the work of many” (Smith 1976, I.i.5). Putting aside the second reason, which is just a story about neoclassical economies of scale, we have what seem to be two distinct benefits of the division of labor, increasing dexterity and technological invention. These two forms of learning by doing may be more similar than at first seems: they are both rooted in expertise.

Smith conceives of dexterity as the acquisition and continual improvement of tacit skills. It is fine-tuning, not obviously recombination. With a narrow focus on simplified tasks, a worker is forced to repeat over and over the same set of operations; and more repetition means more skill, even phenomenal skill.[1] In the case of a line worker, that translates into more operations performed per unit time. This kind of learning by doing seems naturally limited by human physiology, however, and most economists would call it just human-capital acquisition not innovation. But Smith’s point is that every new

[1] Malcolm Gladwell (2008) would agree.

subdivision of tasks recatalyzes this process of fine tuning, implying that the process of subdivision itself enhances productivity: it *is* a kind of innovation.

Mechanical invention for Smith is also a form of learning by doing, albeit one involving perhaps a more conscious or explicit cognition. In becoming narrowly focused and knowledgeable about a specialty, the operative comes to understand the process intimately and is able to perceive ways of simplifying it. Smith also believes that the operative will have an incentive to invent: the utterly apocryphal boy who devised a closed-loop feedback mechanism for steam engines did so in order to free up time to play with his friends (Smith 1976, I.i.8). Obviously, the issues of incentive are more complex, and not merely because Smith is assuming that innovation is *autonomous* (Teece 1986), that is, that the innovation is all under the control of the operative, who does not have to coordinate with other stages of production. Moreover, the innovation is skill enhancing not skill displacing, so it potentially benefits the operative to increase his or her productivity. Smith also assumes that the returns to invention flow to the operative who invents, in the form of increased leisure at the very least. This is probably in part because Smith tended to think of the division of labor as generating separate new “peculiar trades” or “occupations,” which would be coordinated through markets. Incentives for invention by subdivided labor within the boundaries of firms may be quite different.

Through most of nineteenth and twentieth centuries, the idea of technological change conjured up size and complexity. Mass production in dark satanic mills. Steampunk and Rube Goldberg. But for Smith as for Steve Jobs, innovation was about making things simpler, eliminating the inessential. Of course, innovation does make complex things – like iPhones; but it does so by reorganizing tasks and processes so as to make complexity manageable and by hiding complexity within modules and machines.

Notice that so far we have had something that might qualify as innovation without any recombination. Of course, when an operative comes up with a mechanical invention to reduce effort, he or she might well be drawing on ideas observed elsewhere. This could even be true in the process of gaining expert skills in a narrow area (dexterity). As Michael Polanyi (1958, p. 51) understood, the acquisition of tacit knowledge requires not just repetition but also emulating a master. Even learning-by-doing narrowly understood implies the addition of new knowledge and the reorganization of existing knowledge. But this is not "recombinant" in the sense most people mean.

Smith was well aware of the power of recombination, however, and he was also well aware that not all innovation is autonomous: sometimes innovation is *systemic* (Teece 1986). Sometimes it requires simultaneous change in and coordination across multiple stages of production.

> All the improvements in machinery, however, have by no means been the inventions of those who had occasion to use the machines. Many improvements have been made by the ingenuity of the makers of the machines, when to make them became the business of a peculiar trade; and some by that of those who are called philosophers or men of speculation, whose trade it is not to do any thing, but to observe every thing; and who, upon that account, are often capable of combining together the powers of the most distant and dissimilar objects. In the progress of society, philosophy or speculation becomes, like every other employment, the principal or sole trade and occupation of a particular class of citizens. Like every other employment too, it is subdivided into a great number of different branches, each of which affords occupation to a peculiar tribe or class of philosophers; and this subdivision of employment in philosophy, as well as in every other business, improves dexterity, and saves time. Each individual becomes more expert in his own peculiar branch, more work is done upon

> the whole, and the quantity of science is considerably increased by it (Smith 1976, I.i.9).

Scientific knowledge is a good like any other, and it can be produced more efficiently by specialization and narrow expertise. Prescient as this account is, does innovation really come from the industrialized production of knowledge?[2] Because, again, Smith tended to think about the division of labor as coordinated by spontaneous forces, his picture of expert innovation sounds more like Paul David's "open science" (David 2004) than like a corporate R&D lab. Moreover, when invention becomes its own specialty, the division of labor applies to systemic innovation as well as to autonomous. Like the shop-floor autonomous inventor, the professional inventor is able to frame the problem of technological change cognitively, in this case seeing the problem comprehensively, and, by combining together the powers of the most distant and dissimilar objects, is able to solve that problem through recombination.

This Smithian thread was taken up in the 1960s and 1970s by Nathan Rosenberg. In an unjustly neglected paper with Edward Ames (1965), he generalized Smith's account of the division of labor. Ames and Rosenberg noticed that Smith considered only the specialization (or not) of workers, never that of machines. For Smith, the problem is that tools are already specialized, but workers initially are not, meaning that one worker uses

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2 Charles Babbage (1846) would later relate the tale of Garpard Riche de Prony, who was ordered during the French Revolution to produce a table of logarithms. While wandering Paris contemplating in despair the consequences of failure, he happened into a bookstore and thumbed through the *Wealth of Nations*. Thus relearning from Smith what Smith had learned from the French *Encyclodédie*, Prony figured out a way to subdivide and simplify the tasks of calculation so that the necessary operations could be performed largely by a team of hairdressers who had been rendered unemployed by the Revolution (Langlois and Garzarelli 2008). This system produced logarithms quickly and efficiently, but it would not have been able to generate new mathematical knowledge in any obvious way. On the other hand, Teodoridis, Vakili, and Bikard (2017) have shown using the case of mathematics after the collapse of the Soviet Union that a high degree of specialization can lead to rapid advance when knowledge domains are changing rapidly.

many different tools. There are therefore efficiencies to be claimed from specializing workers to the same degree as the tools, which may then lead to further specialization of both workers and tools. When workers become more specialized and tasks more routine and simplified, the skills of those workers become deeper along one dimension; but their set of skills becomes narrower. Writers from Smith himself to Marglin (1974) have thus feared extreme deskilling as the end point of the process.[3] What they failed to appreciate, and what Ames and Rosenberg noticed, is that tools may also change their degree of specialization: they can become *less* specialized. Instead of performing one narrow operation, tools – or, now, machines – can start performing many different operations. However dexterous a human operative can become, a machine can potentially become far more dexterous. The de-specialization of machines is clearly a recombination in some sense, but this sort of mechanization generates increasing returns because it spreads over more and more units the skills effectively programmed into the machine (Langlois 1999).

This means that deskilling – cognitive narrowing in humans – is not in fact the ultimate result of specializing and simplifying tasks. The very processes that lead to efficient specialization of labor – simplification, subdivision, and clear articulation – also make it easier to mechanize tasks, since machines have a comparative advantage in the simple and routine[4] (Simon 1960). The end result is broader skill for both machines and

[3] "In the progress of the division of labour, the employment of the far greater part of those who live by labour, that is, of the great body of the people, comes to be confined to a few very simple operations, frequently to one or two. But the understandings of the greater part of men are necessarily formed by their ordinary employments. The man whose whole life is spent in performing a few simple operations, of which the effects are perhaps always the same, or very nearly the same, has no occasion to exert his understanding or to exercise his invention in finding out expedients for removing difficulties which never occur. He naturally loses, therefore, the habit of such exertion, and generally becomes as stupid and ignorant as it is possible for a human creature to become" (Smith 1976, V.i.178).

[4] Although a notorious hyper optimist about artificial intelligence, Simon also understood economics, and argued that humans would continue to have a comparative advantage in some tasks – those

humans. In many if not most cases, mechanization involves not just a replacement of the human operative with a mechanical version performing the same operations but rather the complete redesign of the production process to best fit machine cognition. The human telephone operator of the early twentieth century was not replaced by an android that could insert plugs into jacks more quickly but by electro-mechanical switching equipment that connected calls in a completely different way. The new technology required users to learn new skills like dialing a phone and looking up phone numbers. It also crowded humans out of the routine activity of call switching into the less-routine activity of designing and maintaining electro-mechanical switches. Although the decreased specialization of machines displaces the existing skills of routine workers, this process simultaneously creates new (and cognitively more complex) specialties for humans, specialties in which those humans acquire skills through learning by doing (Bessen 2015).

Perhaps the most significant way in which Rosenberg developed the Smithian tradition is in seeing innovation as fundamentally about both learning by doing and problem solving. For Rosenberg, most "mechanical productive processes throw off signals of a sort which are both compelling and fairly obvious; indeed, these processes when sufficiently complex and inter-dependent, involve an almost compulsive formulation of problems. These problems capture a large proportion of the time and energies of those engaged in a search for improved techniques" (Rosenberg 1969, p. 4).

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involving high variability and uncertainty, which is to say non-routine tasks – even when computers achieved absolute advantage in everything (Langlois 2003).

Complementarity.

Rosenberg was writing in reaction to the formal representation of the production function, which makes a sharp distinction between technological change (a shift of the curve) and factor substitution (a movement along the curve). If factor substitution requires a significant movement along the curve, asked Rosenberg, can we really believe that the relevant techniques are "known"? Moreover, the formal literature at the time argued that, in equilibrium, technological change should never be biased in any direction, since firms will have the same incentive to reduce costs along one margin as along any other.[5] But the incentives look very different if we see production not in terms of a choice of known "techniques" but in terms of a chain of complementary activities. Innovation then becomes a cognitive process of finding and solving problems. Identify the problems – the bottlenecks in the system – and you have identified the inducement mechanisms and focusing devices that drive technological change.

Although it is probably implicit in Smith, it becomes explicit – and critical – in Rosenberg's view that the productive process is a system of *complementary* activities involving complementary capital goods. "Before the productivity-increasing benefits of any single breakthrough can be realized, many other accommodations need to be made. The expansion of a productive activity runs into a series of new constraints or bottlenecks. As one bottleneck is overcome, others eventually assert themselves and need to be

5 Writing at about the same time, Atkinson and Stiglitz (1969) talked about "localized innovation" with in a production-function framework. But it would not be until fairly recently that the formal literature would take seriously the ideas of biased technological change let alone the representation of production as a sequence of tasks. On this see Acemoglu (2015).

expanded" (Rosenberg 1972, p. 21). The technology historian Thomas Hughes (1983), who thought along very similar lines, called these bottleneck problems *reverse salients*.

Of course, Rosenberg was not the only one to think of technological change in terms of complementarity in production. But this point of view was arguably typical of what I think of as the Stanford School of the economic history of technology.[6] The work of Paul David is about complementarities, and not only in the case of the typewriter keyboard. David (1990) famously argued that the adoption of electricity in American manufacturing after the invention of electric generation technology was slowed by the need to adapt complementary investments, especially the design of factories. David and Gavin Wright (1997) argued that America's success in mining came not so much from any resource endowment as from a network of complementary knowledge, technology, and institutions. And Tim Bresnahan and Shane Greenstein (1996) suggested that the personal computer required complementary "co-invention" by users before it made a significant impact on productivity.

Problem solving in a chain of complementary activities. Is this recombination? Or is it mostly adjustment – fine tuning? Especially in the case of systemic change, innovation typically operates through a process of analogy, which is one manifestation of recombination. In the early automobile industry, the American conception of a horseless carriage competed with, and was quickly supplanted by, the French conception of a road locomotive (Langlois and Robertson 1989). Henry Ford and his associates figured out how to make the latter work on unpaved roads and, more importantly, how to make such

[6] Full disclosure: my degree is from Stanford, and Rosenberg was a member of my dissertation committee.

vehicles cheaply using the moving assembly line, borrowed by analogy from the disassembly lines in slaughterhouses[7] (Ford and Crowther 1922, p. 81). Yet – and this is Rosenberg's point – much of the hard work of innovation came not in imagining the recombinations themselves but in working out all the many difficult problems that inevitably crop up when one tries to combine together the powers of objects that are distant and dissimilar. A lot of innovation is adjustment and fine-tuning, even if, again, some of this problem solving may also take advantage of ideas and practices from other realms.[8]

Modularity.

An *architecture* describes the parts of a system, the roles of those parts in the system, and the nature of the connections among the parts (Baldwin and Clark 2000, p. 77). Loosely and somewhat imprecisely, we can describe an architecture as *modular* if the interactions among the components of the system remain relatively localized (in a well-defined sense).[9] By contrast, a non-modular system would be one in which changes in one component would have effects – potentially unforeseen and complex effects – on many other components, including ones that are distant (in a well-defined sense). In a modular system, interactions are encapsulated within modules; the inner workings of the modules, which may themselves be complex and non-modular, are hidden and sequestered (Langlois 2002), and the modules communicate with one another only through lean and formal interfaces,

7 Mokyr (2002, p. 114) would probably call the borrowing of the assembly line idea not a recombination but a *hybrid*, which means importing another technique whole rather than importing only "subsets of their instructions and epistemic bases" and combining them with existing elements.

8 Just as technological systems are technologies within technologies, so too are they recombinations within recombinations and problems within problems.

9 Technically, what I mean by "modular" here is what Herbert Simon (1962) called *near-decomposability*. What is at stake is more than cutting a system into pieces: near-decomposable modularity means cutting the system into pieces *in a particular way*, one that cleverly partitions interactions and minimizes unnecessary communication among modules.

passing information and materials to one another at what Carliss Baldwin (2008) calls *thin crossing points*.

		Innovation in component functions and designs.	
		Slow	Rapid
Innovation in component interactions and configurations.	Slow	Incremental innovation.	Modular innovation. Langlois and Robertson (1992)
	Rapid	Architectural innovation. Henderson and Clark (1990)	Radical innovation.

Figure 1: Types of innovation. After Henderson and Clark (1990).

What has this to do with adjustment and recombination? Henderson and Clark (1990) famously expanded the traditional categories of radical versus incremental innovation to include two new possibilities: architectural innovation and modular innovation. Architectural innovation means keeping the modules unchanged while varying the way the modules are connected together. A paradigm of this would be Lego© bricks, which can be assembled into an infinite number of complex shapes.[10] Modular innovation

[10] Including, for example, a life-size statue of retiring Red Sox player David Ortiz. Consider also this example of pure architectural innovation from the *Onion* (October 14, 1998): "LOUISVILLE, KY–With great fanfare Monday, Taco Bell unveiled the Grandito, an exciting new permutation of refried beans, ground beef, cheddar cheese, lettuce, and a corn tortilla. 'You've never tasted Taco Bell's five

means keeping the architecture constant while varying the content of the modules. A paradigm of this would be a post-war component stereo system, in which one could constantly swap out amplifiers, pre-amps, speakers, and turntables for improved versions without changing the architecture fundamentally[11] (Langlois and Robertson 1992).

In their (relatively) extreme forms, both types of innovation lend themselves to recombination. This is because, in their extreme (modular) forms, architectural innovation and modular innovation are both kinds of autonomous innovation. Because interfaces are standardized, it is easy to rearrange the pieces and even to incorporate pieces from far-away and unlikely sources.[12] Notice that this is recombination not in the sense of analogy but in the sense swapping components in an out – it is recombination the way DNA does it.

As we move away from the extreme lower left and the extreme upper right of the figure, recombination starts to incur increasing costs of adjustment. In the lower right of the figure, the system becomes less modular: it isn't even clear whether there are distinct modules at all, and every part may interact with every other part. This is arguably what happens in cases of major systemic innovations. It is not surprising that these problems would have been overcome within a single organization, overseen by a single entrepreneur,

ingredients combined quite like this,' Taco Bell CEO Walter Berenyi said. 'The revolutionary new Grandito, with its ground beef on top of the cheese but under the beans, is configured unlike anything you've ever eaten here at Taco Bell.' The fast-food chain made waves earlier this year with its introduction of the Zestito, in which the beans are on top of the lettuce, and the Mexiwrap, in which the tortilla is slightly more oblong."

11 This is not a pure case, of course, as adding wholly new modules is possible and might be considered architectural change. I now have a computer connected to my 1976 Pioneer receiver.

12 I mean "standardized" here in the sense of Baldwin and Clark (2000): that there are explicit protocols to determine whether a module conforms to the design rules of the system. Whether the interfaces are "standard" in the sense of being open or publicly shared is a different matter.

who would have control of all the interdependencies. Interdependencies are a source of what I call *dynamic transaction costs* (Langlois 1992). With learning and a reduced pace of systemic change, we would expect the obvious thin crossing points to emerge over time, leading to increased modularity, reduced adjustment costs, and a Smithian subdivision of tasks, allocated perhaps to separate firms.

Differentiation.

Before there was a Stanford School there was an Austrian School. Beginning in 1871 with founder Carl Menger, the Austrians saw the economy, both production and consumption, in terms of complementary activities and assets (Menger 1950). No one reflected this idea more clearly than Ludwig Lachmann. "All human action, unless prompted by ingrained habit of mind or guided by routine, is problem solving," he wrote (Lachmann 1986, p. 49). For an entrepreneur, problem solving means managing assets in a chain of complementarity.

> *Complementarity* is of the essence of capital use. But the heterogeneous capital resources do not lend themselves to combination in any arbitrary fashion. For any given number of them only certain modes of complementarity are technically possible, and only a few of these are economically significant. It is among the latter that the entrepreneur has to find the "optimum combination." The "best" mode of complementarity is thus not a "datum." It is in no way "given" to the entrepreneur who, on the contrary, as a rule has to spend a good deal of time and effort in finding out what it is. Even where he succeeds quickly he will not enjoy his achievement for long, as sooner or later circumstances will begin to change again (Lachmann 1978, p. 3, emphasis original).

Lachmann distinguished between "*plan complementarity*, the complementarity of the capital combinations of the firm, and *structural complementarity*, the complementarity of capital resources belonging to different firms trading with each other (Lachmann 1986, pp. 63-64, emphasis original).

Rosenberg emphasized salience and commonality along the chain of complements, which leads multiple entrepreneurs and inventors to offer alternate solutions to what were basically the same set of problems. By contrast, Lachmann emphasized distinctiveness and idiosyncrasy, which leads entrepreneurs not only to offer alternate solutions but also to envision alternate *problems*. In the chain of complementarity, process innovation and product innovation are often hard to distinguish, and attacking one kind of problem often yields the solution to a different, and unexpected, problem.

It is easy to find examples in which the solution to a production problem led to a new product. In 1969, Ted Hoff and his team at Intel were trying to find an economical way to make an electronic-calculator circuits for a Japanese client. Producing the necessary hard-wired logic chips would have been too expensive, so they hit upon the idea of a general-purpose logic chip that could be programmed with software (Noyce and Hoff 1981). That became the microprocessor. But Lachmann actually emphasized the opposite pathway. When entrepreneurs vary their products, in an effort to differentiate them from the products of competitors and thus earn rents, they inevitably generate unforeseen problems, which lead in turn to technological improvements, including process innovations. Indeed, for Lachmann, it is product differentiation that drives learning by doing, "the continuous improvement in productivity as engineers and workers come to learn more about what may be done with a given technology."

> In the view currently in fashion this phenomenon has to be regarded as a "gradual shift in the production function," a form of "disembodied"

> technical progress which requires no new capital investment. In our view, by contrast, our phenomenon is primarily a manifestation of dynamic product differentiation. Once a new machine has been introduced, different people will use it in different ways in order to produce different products, or different varieties of the same product, which have to compete with each other for the same customers. It is the divergence of interpretations of the range of potentialities of the new machine which here lends shape and direction to the market process (Lachmann 1986, p. 57).

Recombination is certainly one way of differentiating products and processes. For example, in the 1970s, the noted automotive designer Hal Sperlich had toyed with a "crossover" vehicle with characteristics of both a station wagon and a van. The idea went nowhere at Ford, and Sperling was eventually fired by Henry Ford II. But when former Ford executive Lee Iacocca took over Chrysler, he brought Sperling on board, where Sperling was able to take advantage of the front-wheel-drive K-Car platform to create the minivan[13] (Levin 1995, pp. 82-83).

When recombination occurs in a non-modular way, often through analogy, it leaves in its wake a series of problems needing simultaneous solutions. The transaction costs involved may mean that, by offering a coherent cognitive vision and a full set of *decision rights*, internal organization may be the less-costly mode of organization.[14] When recombination takes place in a more modular way, through DNA-like swapping, the dynamic transaction costs are lower, and markets often have an advantage – or at least less of an early disadvantage.

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[13] Indeed, this is an example Lachmann might have appreciated: the K-Car was an asset internally complementary to Chrysler's plans for the minivan.

[14] By decision rights I mean the right to determine how assets and capabilities will be deployed in any situation not explicitly spelled out in contract (Hansmann 1996; Hart 1989).

Differentiation is a mechanism distinct from recombination, and it has potentially different organizational implications. As the late Steven Klepper (2016) makes clear, the process of differentiation is most often a matter vertical and horizontal disintegration through spinoffs. Looking at examples that included automobiles, tires, lasers, and semiconductors, Klepper found that what appear to be industrial clusters result not from geography but from differentiation. Interestingly, the phenomenon of spinoffs seems to be driven in effect by the same sorts of dynamic transaction costs as vertical integration. Morris Silver (1984) argued that, contrary to the narrative of slippery knowledge dominant in mainstream theory, innovators often discover that that they can't actually persuade others in the chain of complementary activities – those who hold the decision rights – of the value of their ideas. As a result, they must resort to vertical integration as a second-best alternative. Klepper (2016, p. 79) tells a similar story about spinoffs. Innovators within an organization do not spin off a new firm in order to steal intellectual property.[15] Quite the opposite: they typically form new firms because they can't persuade others in the chain of complementarity – others who hold the decision rights – that their ideas for (differentiating) changes in processes, products, or management are valuable. To acquire the necessary decision rights, they must set out on their own.

A tale of three Spragues.

This all may sound rather abstract. To make it more concrete, consider the multi-generational story of the Sprague family of entrepreneur/inventors in electricity and

[15] Which is not to say that intellectual property rights are never an issue in spinoffs. National Semiconductor was founded in the 1950s by four roommates from Stanford, but it was initially staffed by defectors from Sperry Rand. Sperry Rand successfully sued National for patent infringement, and the resulting depressed stock prices allowed entrepreneur Peter Sprague to buy up shares cheaply. On National Semiconductor see below.

electronics. This history not only illustrates alternative pathways for innovation but also provides a window into the history of American industry from the late nineteenth through the late twentieth centuries. The story of Frank Julian Sprague (1857-1934) and Sprague Electric Railway and Motor Car Company illustrates systemic recombinant innovation and the importance of unified decision rights; the story of Robert C. Sprague (1900-1991) and Sprague Electric illustrates modular or autonomous innovation as well as the mid-century model of corporate R&D; and the story of Peter J. Sprague (born 1939) and National Semiconductor illustrates the phenomenon of spin-offs and the disintegration of decision rights.

When he was eight years old in 1866, Frank Julian Sprague and his brother were sent to live with relative in North Adams, Massachusetts when their mother died and their father disappeared to seek his fortune in California.[16] After high school, Sprague traveled to Springfield to sit for what he thought was the exam for West Point; it turned out to be the exam for Annapolis, where Sprague enrolled. Along with West Point, Annapolis in this period was one of the top schools for science and engineering education, and Sprague became obsessed with electricity, a passion he indulged while on shipboard duty, where he sketched ideas for inventions. He began making contacts within the electro-mechanical community, and was lucky to find himself moored at the Newport Torpedo Station, which was a hotbed of electrical innovation under Moses Farmer, the resident "electrician." But

[16] Ironically, the ne'er-do-well David Sprague died in a railroad-crossing accident in 1896. Although Frank Sprague is not as well known to most people as the likes of Thomas Edison and Alexander Graham Bell, historians consider him a major figure in American invention, and several biographies of Sprague and his enterprise have appeared (Dalzell 2010; Middleton and Middleton III 2009; Passer 1952). In the 1950s, the Sprague family commissioned a history, which was published only recently (Rowsome Jr. 2013). Sprague himself also published a number of magazine articles about his work (Sprague 1905, 1934a, b). This account draws on these sources.

the Mecca of invention was Menlo Park, and Sprague eventually resigned his commission to go to work for Edison.

This was the age of the dynamo – the electric generator. By spinning magnets within coils of wire to produce an electric field, a dynamo converts mechanical energy into electricity. But the process is reversible. Applying electric current to the same basic apparatus generates mechanical energy – the electric motor. This was Frank Sprague's real interest, and he eventually persuaded Edison to let him work on it. Sprague's singular idea was essentially to create a closed-loop feedback system that would keep an electric motor operating at a constant speed even as the attached load varied. This was the ideal solution for electric traction. Worried about priority and recognition, Sprague set out on his own, and, with the help of venture capital, started the Sprague Electric Railway and Motor Car Company. (It is striking to a modern reader how similar the world of electrical invention in the late nineteenth century was to that of Silicon Valley, with venture capital, start-ups, and spinoffs. Sprague was essentially a spinoff from Edison.)

The main chance was clear to everyone, and many people were working on it: intra-urban railways. At the time, public transportation consisted mostly of horse-drawn coaches, which were messy, slow, and costly to operate. The arrival of central electric power suggested a recombinant innovation: electric motors coupled with elements of steam railroads to pull the coaches. But the hard part was getting all the elements of that recombination to work and ironing out the kinks: the recombination presented a complex set of bottleneck problems and reverse salients. Initial efforts took the analogy literally. Edison's Menlo Park lab created a test system in which a locomotive, complete with cow catcher, simply swapped a repurposed dynamo for the steam boiler and pulled carriages behind it. As Sprague would eventually figure out, the system needed a complete redesign.

In 1887, a group of entrepreneurs visiting Richmond, Virginia noticed that the city had but one short, lousy horse-drawn tram line. They saw a profit opportunity. Having heard of Sprague from some tests he had run in New York, they approached with the offer of a fixed-price contract to build an entire electric transit system from the ground up, including central power plant, 40 cars, and 80 motors. Sprague jumped at the chance without even visiting Richmond. Given a tight deadline (which in the end had to be extended), Sprague and his team rushed to solve myriad technical problems, most of them unexpected. As the problems mounted, Sprague had to take out personal loans guaranteed against company stock. He had to scale up the Sprague self-regulating motor significantly to deal with grades as high as 10 per cent.[17] He had to figure out how to get power to the motors, settling on an overhead system. In the end, Sprague created a wholly new and modern system design in which the motors, suspended beneath the carriage in line with the wheels, were in the coaches themselves not in a separate locomotive – in effect a simplifying innovation that hid complexity within reorganized modules.

The Richmond system was a success, and Sprague's business took off. So did electrification of mass transit, one of the most rapidly accepted innovations in history. It

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[17] Sprague did not have to integrate vertically into machine shops because the American economy at the time – in another analogue with Silicon Valley – had widespread generic machine-tool capabilities that could be had on contract (Rosenberg 1963). Sprague's main supplier was Bergmann and Company electrical works, part of Edison's supplier network (and also eventually part of GE). The motors for the Richmond system were developed by Brown and Sharpe (working directly with Sprague himself on site in Providence), and other work was done by the Edison shops in Schenectady. As Brusoni, Prencipe, and Pavitt (2001) point out, however, there must always remain at least one stage of production – the design stage, if you will – that retains full decision rights.

created “streetcar suburbs” and altered the economic geography of the city long before the automobile. The rapid growth of electric traction, and of electromechanical technology generally, created tremendous economies of scale and scope, and by 1889 Sprague was forced to surrender his company to Edison General Electric, which had been formed that year under the auspices of Drexel, Morgan & Co. to unify and professionalize Edison’s enterprises. In 1892, EGE merged with Thomson-Houston (which had absorbed Sprague’s principal competitor) to form General Electric. Sprague went on to work on numerous other electrical projects, including elevators, sometimes in cooperation with Edison.

Frank Sprague’s son Robert C. Sprague took after his father: he attended Annapolis and took up electrical tinkering at sea.[18] Frank Sprague’s era was that of the dynamo; Robert’s was that of the vacuum tube and the radio. In some ways the radio evolved from the dynamo, in that Guglielmo Marconi’s transmitters were electromechanical devices that spewed high-frequency electromagnetic energy. The invention of the diode and triode tubes allowed much cleaner reception and eventually transmission. Radio was initially a substitute for the telegraph where wires were impractical, notably at sea. This made it a military technology, and for the duration of World War I the government nationalized American Marconi, the British company that dominated radio early on in the U. S. After the war, the Navy wanted to retain control, but Congress compromised and created a “national champion” – Radio Corporation of America – to take over the assets and personnel of American Marconi as well as assets and radio-related patents from GE,

[18] Robert’s son John L. Sprague (born 1930), who would eventually be President (but never CEO) of Sprague Electric, also became a naval officer, and served in Naval Electronics during the Korean war, after which he received a Ph.D. in chemistry from Stanford. This part of the account draws John Sprague’s recollections (Sprague 1993, 2015) as well as Robert Sprague’s address to the Newcomen Society in 1958 (Sprague 1958).

AT&T, Westinghouse, and other companies. As audio modulation of radio waves became practicable, commercial radio – free broadcast bundled with advertising – was born, and the radio, like the electric railway, became one of the most rapidly adopted innovations in history, faster even than the personal computer. Like the personal computer, the radio benefited from a thick network of hobbyists; and like the personal computer, the radio was a relatively modular technology in which a fairly standard set of discrete components could be combined cheaply, implying low economies of scale in assembly (Langlois 2013).

While still on active duty in 1925, Robert Sprague came up with an idea for a tone control for the radio in the form of a switchable bank of capacitors. He and his wife Florence started producing them out of their kitchen in Quincy, Massachusetts. Sales were disappointing. But Robert's brother Julian pointed out that the capacitors in the tone control were themselves small and well designed. These sold well, and Sprague Specialties (eventually Sprague Electric) formed in 1926. Attempts to outsource production of the capacitors "didn't work out as planned" (Sprague 1958, p. 11), so the family had to set up their own assembly operations. By 1929, they needed space, and essentially by accident ended up in Frank's old home town of North Adams, where they bought a disused textile mill.

Sprague Electric was not a managerial multi-divisional enterprise of the sort Alfred Chandler held out as characteristic of American industry. Closely held until the very end and always functionally organized, Sprague came closer to what Chandler (1990) called personal capitalism.[19] Yet in many other respects Sprague epitomized the American

[19] Even though Sprague Electric joined the Fortune 500 in 1962, its stock was not listed on the New York Stock Exchange until 1966, though it had been sold over the counter for some 20 years (Sprague 2015,

manufacturing firm of the mid-twentieth century. The company initially focused on capacitors, a discrete "passive" component essential to all electronic systems of the era, including the digital systems that would evolve after World War II. Sprague was highly vertically integrated, making not only capacitors (and eventually other passive components like resistors) but also making its own fabrication machinery. This was largely because the company's strategy focused on quality and rapid generational innovation rather than price. Sprague established an R&D lab in North Adams to stay one step ahead in capacitor technology, which usually meant inventing production equipment as well. This was the classic mid-century model of R&D-driven innovation, successful in this case because highly focused. This kind of innovation certainly involved applying science – what Joel Mokyr (2002) calls "propositional" knowledge. Discovering new materials and processes for making capacitors also certainly involved some kinds of recombinant knowledge, and fabrication is a complex process with bottlenecks and reverse salients. Yet in the large – from the perspective of electronic systems – this was fundamentally fine tuning: figuring out how to produce capacitors at increasingly lower cost with increasingly superior specifications.

Alexander Field (2012) has argued that the 1930s were the decade of highest productivity growth in the twentieth century. Perhaps the Sprague experience illustrates why: Sprague responded to the Depression by hiring a management-consultant firm to redesign factory processes and compensation schemes, and it pared expenses while temporarily halting R&D. Unsurprisingly, World War II was a bonanza for the company.

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p. 77). Sprague had financed its original mill in North Adams in part by selling equity to local business people, and it sold some stock at low prices to employees.

By the end of the war sales had increased eight fold and employment more than doubled. The war also propelled Sprague into products beyond capacitors. (They had even teamed up with a local shoe firm to make gas masks.) Business declined when the war ended, but quickly picked up again as the Cold War and new technologies like FM radio demanded components. The Wagner Act forbade company unions, and Sprague's workers required a second try before creating a union that, although independent of the national labor organizations, was deemed kosher by the feds. Despite some unrest before the war and again in 1946 (when the repressed inflation of the war burst into view), labor relations at Sprague were calm throughout the post-war years, and the firm provided an array of mid-century-style paternalistic benefits.

The birth of the transistor in the early 1950s was not initially a disruptive innovation, since transistors simply substituted for vacuum tubes in circuits that still required many discrete passive components. Like other electronics firms, however, Sprague hoped to get involved in the transistor revolution, and was one of the firms that bought rights (inexpensively) from Bell Labs. It is one of the central facts of the history of the semiconductor industry in the twentieth century, however, that the electronics firms that were most successful in the vacuum-tube era could not translate that success into the era of the transistor (Langlois and Steinmueller 1999). Sprague was no exception. The company set up a semiconductor production division in Worcester, Massachusetts. But, though company scientists did make some important contributions to the technology, the semiconductor strategy was unfocused and drew resources away from the cash-cow passives businesses.

By the 1970s, the world was changing for most traditional American firms. Foreign competition, which had been almost non-existent right after the destruction of World War II, began to resume in earnest. The Vietnam-War inflation garbled price signals and would soon precipitate the collapse of the Bretton Woods system, increasing international flows of goods and capital. In a set-piece repeated throughout American industry, the Sprague workers, who had finally affiliated with the AFL-CIO a few years earlier, responded to inflation by staging a major strike in 1970 in the midst of a recession (Seider 2014). Sales plummeted, and Sprague, like other American firms, accelerated the process of moving labor-intensive activities to the South and overseas. North Adams collapsed into decline. At the same time, many American firms were flush with what Michael Jensen (1986) dubbed free cash flow, the rents of America's post-war success. These firms cast about for things to spend their money on, creating the conglomerate era of unrelated diversification. Sprague was an appealing target. After a near-miss with a merger to a similarly sized firm, the company was gobbled up first by General Cable in 1977 and then by Penn Central in 1981. When inflation subsided and foreign competition intensified, conglomerates were forced to get rid of unrelated units. Penn Central spun Sprague off in 1987; and, amid mounting losses, the company was finally pieced out completely by 1991. The former textile mill in North Adams that was once Sprague's main plant is now the Massachusetts Museum of Contemporary Art.

Why were the traditional electronics firms unsuccessful in semiconductors? Essentially because the model of product and process innovation through corporate R&D

was the wrong model.[20] Once the transistor effect had been demonstrated at Bell Labs, the crucial reverse salient was *production*: how to fabricate the devices cheaply and reliably. It was a classic learning-by-doing problem. And it turned out that highly specialized start-ups were best equipped to solve it.

William Shockley, one of the inventors of the transistor, decided to leave Bell Labs and set up shop on the San Francisco Peninsula where he'd grown up. Shockley was a great recruiter of personnel but a terrible manager and by all accounts an unstable personality. When he decided to turn away from the problems of production in an attempt to invent new devices, his best staff members revolted. The "traitorous eight," as they were famously called, secured venture capital from Long Island investor Sherman Fairchild and set up shop on their own. One of the eight, Jean Hoerni, figured out a way to create transistors by sequential deposition – the planar process – and his colleague Robert Noyce extended the idea to fabricate multiple transistors on a single substrate – the integrated circuit. In many ways the planar process was a recombinant innovation. Hoerni's breakthrough came because he went against the conventional wisdom and tried leaving an oxide layer on top of the wafer. He discovered that the oxide was in fact a terrific insulator; and by combining this insight with several diffusion processes already well known at Fairchild, he created a new and vastly superior way to fabricate transistors (Lécuyer 2006, pp. 150-152).

[20] Rather than engaging in traditional corporate R&D seeking new knowledge, spinoffs like Fairchild and Intel followed what Robert Noyce called the principle of "minimum information" – do research only when you run into a roadblock and have no other choice (Moore and Davis 2004, p. 20).

The problems involved were arguably a more complex version of the kinds of problems Sprague had had to solve in fabricating capacitors. But not only did Noyce and company make the crucial breakthroughs, they were also highly focused on price and performance not product innovation, and they were unencumbered by the baggage of capabilities and investments in other technologies. Thus what started as a recombinant innovation proved successful as a trajectory for fine tuning. Under production manager Charlie Sporck, Fairchild began mass-producing semiconductors using the planar process, employing the same kind of learning-curve pricing Henry Ford had once used with the Model T (Lécuyer 2006, p. 200-207).

But Sherman Fairchild had a buyout option. This he speedily exercised in 1959, turning the successful start-up into the West Coast division of his Fairchild Camera and Instrument Company. The change in ownership structure – in decision rights – immediately led to conflict. Not owners, and without stock options, the engineers were no longer being rewarded. Perhaps more importantly, they felt that the new owners did not understand what it took to be successful in the semiconductor business. Referring to the company's distant Long Island headquarters, Charlie Sporck recalled that "the Syosset folks were using large profits generated by semiconductor operations to fund acquisitions that didn't make a lot of sense. There was a growing friction between the division's management and the Fairchild corporate management" (Sporck 2001, p. 139). Soon Fairchild staff were defecting in droves to create their own start-ups, fueled by venture capital. Far more than agglomeration economies, it was these spinoffs that created Silicon Valley (Klepper 2016; Moore and Davis 2004).

When Julian Sprague died young in 1960, his son Peter was left with a small inheritance. An adventurer and entrepreneur by inclination, Peter was not an engineer like his uncle and cousin but had studied political science at Yale and MIT and economics at Columbia. While working in New York in 1964, he invested in a small, near-bankrupt firm called National Semiconductor that was operating out of a former hat factory in Danbury, Connecticut. By 1966 he had taken the company public on the cheap and was chairman of the board.[21] For the third generation, a Sprague was head of an electronics firm by age 27. Charlie Sporck soon came calling with a group of defectors from Fairchild, looking for a company that would give them the decision freedom they had lacked. "I proposed a plan," wrote Sporck in his memoirs, "wherein I would bring some competent people from Fairchild with me, and we wanted complete decision making authority, along with a free rein to turn the company around" (Sporck 2001, p. 211). Overcoming some initial misgivings, Sprague cleared the way by firing some of the existing staff, and the board installed Sporck as CEO, giving him *carte blanche*. And stock. This arrangement was an early template of the Silicon Valley firm (Lécuyer 2006, pp. 259-261).

Sporck immediately cut employment in Danbury and moved the company's center of gravity to the Peninsula. National became a cost leader in the production of semiconductors through tight operational controls, outsourcing final assembly to the Far East. By 1975, the company was a "super-mass-production manufacturer" – the largest producer in California and the second largest (after Texas Instruments) in the U. S. (Lécuyer 2006, pp. 291-292). In 1987, National acquired what was left of Fairchild,

21 Interview with Peter Sprague, November 13, 2012, Silicon Genesis oral history project, Stanford University Libraries. Available at http://silicongenesis.stanford.edu/stanford_video/sprague.htm. Accessed March 19, 2017.

eventually selling it off again in pieces at a profit, though by that time National was losing its cost advantage to Asian competitors and had begun focusing on its niche of linear rather than digital ICs (Sporck 2001). In 2011, National itself was acquired by Texas Instruments for $6.5 billion.

Perspective.

Yes, innovation often involves recombination. That was true of the electric railway, of capacitors, of the planar process. But these recombinations – the contours of which were often "in the air" – all threw up arrays of complementary problems that had to be solved from the bottom up: especially when innovation is non-modular, recombination requires fine-tuning and problem solving to be successful. Sometimes it is the bottom-up process of problem solving that shows the way for new recombinations.

In a non-modular environment, problem-solving along the chain of complements requires the synoptic vision Adam Smith described. It also requires unified decision rights, often implying vertical integration or at least a synoptic design stage with wide rights of control. Innovation also occurs through differentiation – fissioning and forking away from established ways of doing things. This kind of innovation also requires cohesive decision rights, achieved by spinning off a new ownership structure. Vertical integration and spinoffs are the two faces of the problem of dynamic transaction costs.

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