Generality, Recombination and Re-Use

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Abstract

I study the economic conditions relevant to the emergence of new general purpose technologies, and, more generally, to inventions which will be recombined or otherwise re-used. The decentralized distribution of knowledge about technical and market opportunities *ex ante* is central to my analysis. Changes in the distribution of knowledge caused by the market presence of early inventions play an equally important role, particularly when they convert entrepreneurial knoweldge into market knowledge. I apply this analysis to the history of invention of computer technologies for white collar work automation.

Motivation and Key Findings

Economists have long noted the benefits to society of recombinant technical change and of general purpose technologies.[1] Recombinant technical change is the re-use of existing

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[1] See for example Schumpeter (1939), Nelson and Winter (1982) ,Weitzman (1998), Romer (1987), Bresnahan and Trajtenberg (1995) and my chapter in the Handbook of the Economics of Innovation and Technical Change.

innovations in new areas; Schumpeter was probably the first to point out that most technical progress is recombinant. General purpose technologies are (1) widely used, (2) capable of ongoing technical improvement, and (3) enable complementary innovation in application sectors (AS)[2]. Both recombinant technical change and GPTs involve re-use. From an ex post, normative, standpoint, re-use creates dynamic social increasing returns to scale and scope.[3] This paper takes an ex ante, positive standpoint and examines the economic conditions conducive to original invention of re-usable inventions. A central question is the knowledge available to the inventor, at the time of initial invention, whose work will later be recombined or lead to the emergence of a new general purpose technology. Does such an inventor know of future uses, including uses that depend on future invention or even the future creation of new markets and industries?

Recent investigations have deepened our understanding of the logical relationship between re-use and growth theory, and have shown the importance of GPTs in the industrial revolution, the second industrial revolution (in particularly impressive depth), and the information age[4]. Recombination and GPTs can make re-use into a powerful force for economic growth based in increasing returns. Note that this is a normative, *ex post*, perspective. Once technologies that can be widely recombined have been invented, once a GPT has been invented and is leading to the further invention of valuable applications, the economy is gaining the benefits of social increasing returns to scale.

In this paper I focus attention on a new set of corresponding *ex ante,* positive, questions about the origins of GPTs and the origins of technologies that will later be recombined. The original invention of a technology that will be widely re-used is an important economic event because of the spillovers that flow through re-use.

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[2] See my Handbook chapter (cited above) for more detailed definitions in the literature.

[3] I note that the language "increasing returns to scale and scope" implies a normative (benefits) framework not a positive one, and similarly that the language "social increasing returns to scale" implies a normative (cooperative) framework rather than a positive (information, incentives, and in this paper, knowledge) framework. I note also that these benefits assessment frameworks are ex post, i.e., recombination, re-use, and generality of purpose are all excellent sources of social gains if they can be achieved.

[4] See sources in my Handbook chapter (cited above) and also in Jovanovic and Rousseau (2005).

How, ex ante, are inventors to identify technologies that will be re-used or will be general in purpose? Knowledge of what is technically feasible is not sufficient to answer these questions. They are questions about the overlap between the technically feasible and the valuable for a wide swathe of the economy. I examine the case, which I will argue is very important empirically for technical progress in white-collar-work automation (WCA), in which that knowledge is scarce *ex ante*.[5]

I distinguish between two kinds of knowledge, separating *entrepreneurial knowledge* from the more usual technical and market knowledge. Technical knowledge is a firm's knowledge of its own production possibilities: in a standard market model, all a firm needs to know is its production possibilities and prices. I am going to take a slightly wider view than "prices" or what firms can know about markets; for example, firms can know what product varieties are available. Entrepreneurial knowledge is, in contrast, is knowledge of other firms or industries held in a particular firm or industry. In the simplest example, a clear engineering plan to build a new mousetrap would be technical knowledge, while knowing whether the world will accept it as better and beat a path to your door is entrepreneurial knowledge. (This is Hayek's definition (Hayek (1945).) I construe technical knowledge to include knowing the research and development cost of a particular invention project; knowing which of a number of potential product innovation projects will be attractive to customers, even knowing who the relevant customers might be, is entrepreneurial knowledge.

The point of emphasizing entrepreneurial knowledge is that a market economy typically has highly distributed technical knowledge. If each agent knows her own business' invention opportunities and technical needs but not those of other firms or industries – the information requirements needed for a neoclassical economy with price-taking supply – that is distributed knowledge. In this sense, the more distributed is knowledge, the scarcer is entrepreneurial knowledge. This matters for re-use when the knowledge needed to anticipate later uses is

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[5] In this regard I follow a long tradition in the analysis of technical change. Like Rosenberg (1996) I emphasize uncertainly and depart from the "linear" model in which science causes technology which in turn causes application and growth. Yet I also depart from models like that of Acemoglu (2002) in which demand needs are known and directly influence inventors choices.

not available to an early inventor.

To analyze recombination and GPTs is to consider a world in which there are multiple potential inventors. This leads me to focus on cases in which the economy is decentralized and the resulting potential scarcity of entrepreneurial knowledge is that one potential inventor need not know another potential inventor's circumstances. The inventor of a potential general purpose technology might not, for example, know of the prospects for complementary innovation in applications sectors. Symmetrically, a potential application sector may not know of technical opportunities in what would be, if only it were to be invented, a GPT industry. This kind of scarcity of entrepreneurial knowledge can reduce the ex ante return to innovation.[6]

The second building block of my analysis concerns the way the knowledge state of the economy changes when invention occurs. Suppose once again that ex ante two potential inventors - a GPT inventor and an applications inventor, or an original inventor and a recombiner – do not know of one another's technical possibilities. If, however, one of them has invented something and commercialized it, the other can learn of it. This lessens the scarcity of entrepreneurial knowledge as the second inventor now can look at the first invention and consider whether to make a complementary invention. Of course, the search and information processing need not be costless at this stage. I assume that invention and market presence creates market knowledge, not necessarily complete and perfect market knowledge.

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[6] It is a common feature of many economic models of inventions that different inventors have different knowledge. This feature is shared by Schumpeterian models (earlier and later inventors have different knowledge, the later may creatively destroy the future) GPT models (GPT and AS have different knowledge needed to work together) recombinant models (ideas become more valuable when combined with other ideas) and standard models of optimal patent policy (early invention and improvement based in different knowledge.) The same structure is used in models of organization; each of two agents making complementary innovations has distinct abilities and knowledge.

Another common feature of economic models of invention is the accumulation of a stock of knowledge. Early inventions pave the way for later inventions. Models of quality ladders, for example, assume that each level of quality cannot be invented until after the last level. Models of recombination assume that ideas, once made, can be combined with other ideas in potentially useful ways.

Many of these literatures have been pushed much farther than I attempt here. My goal, however, is to examine the specific problem of scarce entrepreneurial knowledge.

One mechanism by which this might work is if a potential GPT is invented and marketed "on spec," potential applications sector inventors learn of its existence. Entrepreneurial knowledge is then less scarce, and complementary innovation in the AS can be based on market knowledge of the GPT product. I will call that particular mechanism a "planned initiative." Note that a planned initiative does not require much entrepreneurial knowledge at the interim stage. It does require, however, entrepreneurial knowledge ex ante, as the GPT innovator must know what kind of GPT product would appeal to applications sectors. I use "must know" there in an economic sense: the GPT inventor must have a good enough idea of whether AS will follow profitably to invest in a specific technical direction. I will argue that, as a historical matter, planned initiatives are scarce in WCA precisely because this kind of broad based entrepreneurial knowledge is typically scarce.

When the original problem was difficulties in seeing precise overlaps between technological opportunity and demand needs, early invention and commercialization can create market knowledge of a number of forms. One is that technologists' knowledge of demanders' needs can be converted from scarce entrepreneurial knowledge into widespread market knowledge. Technologists can now learn, by observing what demanders buy, knowledge of what demanders want. A body of demand, once created in a market, can be studied and thus served. An early specific technical solution, even if far from optimal (given all knowledge by both technologist and demanders) can create sufficient market knowledge to enable movement in the direction of optimality. Seeing that a demander is using technology with features G, a technologist can inquire about the marketability of features $G + \Delta g$. It such an enquiry is difficult ex ante, but feasible at the interim stage, valuable market knowledge has been created. Symmetrically, the commercialization of a specific technical product can create knowledge on the part of demanders about what is technically feasible. Demanders could then undertake experiments to see what co-invention works effectively. The results of those experiments are valuable market or technical knowledge; if the results suggest new directions to technologists, they represent an update in the market knowledge of the economy. The fact that demanders needed to undertake experiments can make it very difficult to have complete ex ante entrepreneurial knowledge. A related situation arises when demanders can only understand what a new technology can do by seeing it demonstrated. Their invention of useful applications (which was contingent on the creation of a working prototype technology) can suggest new directions by showing where the overlaps between the technically feasible and the socially desirable.

These simple examples, and the more complex examples we review in the industry history section, reveal that in an economy with distributed knowledge, overlaps between the technically feasible and the socially desirable sets of inventions can be "unknown" in the sense that no individual knows them well enough profitably to direct specific technical investments, and "unknowable" in the sense that either (i) the relevant holders of distributed information need not know one another's technical needs and capabilities with adequate specificity or (ii) detailed good faith discussions among the relevant knowledge holders need not lead to successful communications because the possibility of dual invention is too hypothetical. Initial inventive steps can make the locus of the overlap more known (and more knowable) by converting entrepreneurial knowledge into market knowledge.

Recombination

Economists have already recognized that recombination involves the possibility of knowledge scarcity. Weitzman (1998), in a classic model of recombinant growth, has a model in which the number of "seed" ideas is increasing over time as a result of R&D and "seed" ideas can be recombined into potentially valuable inventions. Weitzman's elegant analysis shows first that the combinatorics of mixing and matching an increasing number of ideas can lead to faster-than-exponential expansion of the stock of possible useful inventions (thus easily overcoming diminishing returns.) As the number of seed ideas grows, however, the information-processing costs of finding recombinant matches also grow without bound, providing a limit on the growth process. Weitzman's model has no treatment of entrepreneurial knowledge, however. A number of management scholars have taken up the question of search to create recombinant knowledge: a classic study is Fleming (2001), who notes that common knowledge of what technologies are economically related can change over time, and uses the framework of "local" knowledge as related to commercial exploitation of ideas, while "distant" search is exploratory and potentially creates hitherto unforeseen combinations.

An important related notion is that certain kinds of knowledge can come to be science, and that this has important implications for the scope of entrepreneurial knowledge in the economy. Mokyr (2002), for example, makes the important observation that the representation of technical knowledge as science during the industrial revolution in England together with the institutions of open science, lowered the costs of widespread "access" to knowledge. If the solution to the problem of scarce entrepreneurial knowledge is better representation of knowledge, then there is, as Jones (2009) points out, a "burden of knowledge." This suggest an arc of possibility (not unlike the simpler Weitzman arc) in which improving access first improves the ability of the economy to recombine different kinds of knowledge and then creates congestion.

I discussed the economic importance of recombination above. In this section, I model the distinction between different kinds of knowledge ex ante and ex post a first invention which may later be recombined. Potential inventors, the only actors in the recombination model, are endowed with technical capabilities and market knowledge, which permit them to make productive inventions at a cost. Potential inventors are also endowed with knowledge about the possible productive applications of their technology. Their entrepreneurial knowledge (or its lack) arises with regard to knowledge about one another.

Payoffs

We first model the simplest problem in which recombination and re-use can occur, that of two potential inventions, named T_j and T_k. The R&D expenditure needed for T_j is

r_j. If a potential inventor j invents T_j, we write $a_j = 1$, else $a_j = 0$. There is a large number of potential inventors of both j and k, so that invention will occur if the expected net return to the invention is positive. The (total) value which is produced is $V(T_j)$ if only j is invented and $V(T_j, T_k)$ if both are invented. The case of recombination or re-use arises when $V(T_j, T_k) > V(T_j) + V(T_k)$, so unless otherwise noted this is assumed.

This is a very stylized example, and the increase in value $V(T_j, T_k) - V(T_j) - V(T_k)$ is meant to capture several different notions of commonality. One is that j is a GPT and k is its first (and as far as sometimes can be foreseen, only) application; then the increase in value arises because the technologies are complementary in production in the k sector. Another notion captured by the increase in value is that j and k are two different industries, and that an invention (either) one makes is valuable for the other, after the other makes a further technical investment to recombine it.[7] A related notion is that there is some part of T_j which can be used in industry k (and/or of T_k which can be used in industry j) such as a common component or idea.

Note that I do not assume that there is some kind of technological hierarchy in which j must be invented before k or vice versa. This assumption is common in the appropriability literature but is not suitable for my purposes.[8] An idea which is valuable in two uses might be invented first for either of them; it can then be recombined into the other.

Appropriability

Each inventor gets a claim c_j if she invents. Claims determine how inventors share the ultimate value created. These claims reflect not only the formal patent system, but also the openness of the innovation system more generally, the value of first mover advantages, and so on. If only one potential inventor, j, invents, the share is $\lambda_1(c_j) \leq 1$. The subscript

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[7] For this interpretation one might also write that the first invention lowers the costs of the second. Since that is equivalent, and since it is convenient to work with the distribution of r_j in what follows, I write value-increasing as including cost-reducing.

[8] See Scotchmer (2004) for a review of a number of models with this assumption. Technological hierarchy may provide a reason to prefer stronger appropriability for earlier inventors or to oppose openness, an effect omitted from my analysis.

1 refers to the fact that j is the first inventor. This share can be less than 1 if there is competitive imitation. The share can also be less than 1 if there are strong patents, and exploitation of patents involves market power (even if temporary).

More generally, if there are multiple inventions, C is the list of claims, the shares are $\lambda(C)$ and the inventor with the claim in ith position gets $\lambda_i(C)$.If j invents first and k second, they each have a claim on the total value that is produced, j gets $\lambda_1(c_j, c_k)$ and k gets $\lambda_2(c_j, c_k)$. The determination of these shares depends on the factors discussed above, and also on the bargain struck by j and k if each has a claim on the other, and thus depends on the system of patents or trade secrets, the information j and k have about one another after they have invented and on all the other myriad determinants of the return to innovation.

It will be useful to assemble all of the appropriability shares relevant to j and call them $\lambda^j(C)$. This is $\lambda_1(C)$ when $C = c_j$, $\lambda_2(C)$ when $C = c_k, c_j$, and so on.

Knowledge

The novel element here is a distinction between two kinds of knowledge. I distinguish between the technical knowledge of each sector and the entrepreneurial knowledge which has the possibility of creating new markets.

Each potential inventor j or k knows the menu of products it could provide and how much it will cost. That is *technical knowledge* – technical knowledge, at least locally, is very good in this model (though it may be expensive depending on r_j or r_k). A potential inventor also knows about the local demand for the invention, i.e., j knows the probability that value $V(T_j)$ will be created if j is the only inventor. However, j may not know whether her invention is useful to k or that k might be able to invent something that is useful to her. Knowledge about the possible future gains from trade, outside current markets and connections, is entrepreneurial knowledge. I follow Hayek (1945) in making the division between local market or technical knowledge, knowledge about one's own existing business, and entrepreneurial knowledge, knowledge of potential new connections. The key point about entrepreneurial knowledge is that it only matters before the creation of a new connection. In my framework, once something has been invented and commercialized, knowledge of it is market knowledge. By that I mean that it depends on what others in the economy are doing, not what they might be doing in a hypothetical future. As a formal matter, this means that invention changes the knowledge state of the economy.

To write down a potential inventor of j's expected profit from inventing T_j in the very simple example of this section, I need only consider knowledge by one kind of agents in two states, (a) no one has yet invented and (b) T_k has been invented. Thus in this example $K_j(T) : I^1 \Rightarrow R^2$. More generally, the domain of K_j is inventions, so T is a list of all the inventions that have already been made. The range of K_j is outcomes, in which T_j is one of the inventions. Since we will consider examples with more inventors in the next section, I write it slightly more generally as $K_j(T) : I^{J-1} \Rightarrow R^{2^{J-1}}$.

In the 2-technology example, initially, each j-agent has a $K_j(0)$, which is their *ex ante* probability that (1) $V(T_j)$ will come into existence if they spend the r_j and nothing else happens, (2) both j and k will be invented, and $V(T_j, T_k)$ will come into existence.

This knowledge is a mixture of local and entrepreneurial, i.e. $K_{j\{j\}}(0)$ is about j's business or industry but $K_{j\{jk\}}(0)$ is not local, concerning both j's business or industry and k's, thus I classify it as entrepreneurial knowledge. Finally, each agent also has a $K_j(T)$ which arises if other agents have invented T. If T_k has been invented, it is no longer entrepreneurial knowledge for someone in sector j to know about it. It is now market knowledge. Market knowledge may or may not be perfect, but in what follows I will typically assume that market knowledge about the same outcome is better than entrepreneurial knowledge.

Agent	Local, Technical K	Market K	Entrepreneurial K
j	I might invent T_j	You have invented T_k	You might invent T_k
k	I might invent T_k	You have invented T_j	You might invent T_j

Payoffs $V\lambda K - r$

In an incentives model, we write the payoff to an inventor as $V\lambda - r$, where V is the value created, λ is the portion captured by the inventor, and r is the up-front R&D cost. Information enters through the determination of λ and of V. If there is bargaining when two inventors have claims, their information about one another after they have met and done due diligence is a determinant of λ, and their information about demand and cost can be a determinant of V and r. Information also enters in a different way here: scarce entrepreneurial information means that potential inventor j doesn't know of potential inventor k's identity, doesn't know exactly which of a number of technologies that might be complementary is both feasible and a fit, and so on. The possibility of incomplete entrepreneurial information converts the typical profit calculation of form $V\lambda - r$ into one of form $V\lambda K - r$.

We can use the two-firm (recombinant) example to understand this, especially to understand the conversion of entrepreneurial information into market information. In the two-technology example, if T_k has already been invented then the only question is about T_j. We write π_{jS} ("S" for second) as the payoff in that contingency.

$$\pi_{jS} = V(T_j)K_{j\{j\}}(T_k))\lambda_1(c_j) + V(T_j, T_k)\lambda_2(c_j, c_k)K_{j\{jk\}}(T_k) - r_j \tag{1}$$

that is, we evaluate V, λ and K under the assumption that T_k has already been invented. There is a symmetric expression for k if T_j has already been invented, π_{kS}. Note that the first term anticipates the possibility that j anticipates total returns of only $V(T_j)$ even though T_k has been invented. This suggests that invention by k need not perfectly inform j. This is the case emphasized in the "absorptive capacity" and "recombinant search" literatures, which treat the problem of a firm learning about knowledge which already exists outside it. In this paper, I am more concerned with the ex ante first invention, and less with the problem of learning about existing knowledge.

At the first stage, we write π_{jF} first in longhand and then in a general notation. At the first stage, information about both local/market outcomes and entrepreneurial knowledge is relevant. The probability $K_{j\{j\}}(0)$ is entirely local, but the probability $K_{j\{jk\}}(0)$ is entrepreneurial – it is the probability that k will invent if j does.

$$\pi_{jF} = V(T_j)K_{j\{j\}}(0))\lambda_1(c_j) + V(T_{j,}T_k)\lambda_1(c_j, c_k)K_{j\{jk\}}(0) - r_j \tag{2}$$

$\pi_{jF} = V(T_j; T) \cdot (\lambda^j(C) \circ K_j(0)) - r_j$

and symmetrically for k. Note that the first-stage expected value is an inner product $(\cdot)$ since there are two potential final outcomes. Within each final outcome, we multiply λ times K element by element $(\circ)$. This notation will be more useful when the inner product is longer. But for now I use it to point out that we could write both equations (2) and (1) in the same notation:

$\pi_j = V(T_j; T) \cdot (\lambda^j(C) \circ K_j(T)) - r_j$

Where to evaluate π_{jF} we set $T = 0$ and $C = c_j$, and to evaluate π_{jS} set $T = T_k$ and $C = c_k, c_j$. Obviously this shortcut will be more valuable for a longer list of inventions.

While they are written in a common notation, there are important differences between first and second. Note that three things have happened as a result of the earlier invention, one each to V, λ, and K. V is larger to the extent there are complementarities. λ is smaller to the extent the first inventor has a claim which lowers λ_2. Finally, there is market knowledge about the technology invented earlier. This need not be perfect; $K_j(T_k)$ is what j knows, and need not know of T_k, though under open-information j will have the opportunity to know of k.

Equilibrium

Both invented: Either j is invented first and then k or vice versa:

$\pi_{jS} > 0 \quad \text{and} \quad \pi_{kF} > 0 \quad \text{or} \quad \pi_{kS} > 0 \quad \text{and} \quad \pi_{jF} > 0$

Neither invented: $\pi_{jF} \leq 0 \quad \text{and} \quad \pi_{kF} \leq 0$

Only j invented $\pi_{jF} > 0$ and $\pi_{kS} \leq 0$ and $\pi_{kF} \leq 0$

Only k invented $\pi_{kF} > 0$ and $\pi_{jS} \leq 0$ and $\pi_{jF} \leq 0$

The point here is not that there are these four outcomes but that there are distinct reasons in value, appropriability, and information, to reach or not reach each outcome. That leads us to the examination of some special cases to clarify the role of entrepreneurial knowledge.

Bottleneck is incentives, not entrepreneurial knowledge

Let us first consider the case, familiar in the literature, in which there are no problems of entrepreneurial knowledge ($K = 1$). In this case, we can interpret V as a risk-adjusted expected value and interpret $\lambda(c_j, c_k)$ as the outcome of an ex post invention bargain between two inventors, limited by their appropriability claims and by imitation. Then write[9]

$$\pi_{jF} = V(T_j)\lambda_1(c_j) + V(T_{j,}T_k)\lambda_1(c_j, c_k) - r_j$$

and

$$\pi_{kS} = V(T_k, T_j)\lambda_2(c_k, c_j) - r_k$$

This (very) stylized model shows classical incentives results about the private vs. social rate of return to innovation. The interesting case arises when joint invention is economic but only if it is joint: $V(T_k, T_j) > r_j + r_k; r_j > V(T_j); r_k > V(T_k)$. Because of this complementarity, the private return to innovation is less than the social return to innovation. If we assign claims to a first and second inventor such that $\lambda_1(c_j) = 1$ and $\lambda_1(c_j, c_k) = 0$, then no invention takes place in equilibrium. Only if j has a claim which covers part of k's value (via patent, trade secret, market position, or other mechanism) and thus raises $\lambda_1(c_j, c_k) > 0$ by a sufficient amount is it in her interest to invent. This model also shows that too large a claim for the first inventor can lower $\lambda_2(c_k, c_j) < r_j / V(T_{j,}T_k)$ and thus prevent equilibrium invention[10]. The model shows more generally that claims to both inventors in particular

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[9] There is another pair of inequalities symmetrically for the k, j order of invention, but j and k are j are simply names of two inventors in this model.

[10] Note that there is nothing in the model to suggest any priority in terms of claims for earlier inventors.

size ranges support efficient invention.[11]

This model also suggests that ex ante bargaining by the two potential inventors will work to support invention. The problem, for example, of excessively small $\lambda_2(c_k, c_j)$ arises only because k might seek to hold up j based on k's claim c_k. Since the two potential inventors know of one another ($K = 1$) one can easily suppose that they get together and, for example, form a single firm to internalize the externality of their two inventions; one invents first, and the other recombines into a high-value use. That does not much resemble the "recombination" discussed in the literature, which is part of my point. We now turn to a model in which the opportunity to recombine is a surprise.

When bottlenecked by K

The absence of entrepreneurial information ($K_{j\{jk\}}(0) = 0$) is sufficient to prevent any investment when only joint invention is economic: $V(T_k, T_j) > r_j + r_k; r_j > V(T_j); r_k > V(T_k)$. It is easy to see there will be no first invention as $\pi_{jF} = V(T_j)\lambda_1(c_j) + V(T_j, T_k)\lambda_1(c_j, c_k) * 0 - r_j < 0$ and symmetrically for k for all $\lambda_1 \leq 1$. The problem here is that valuable invention is not undertaken because it only becomes valuable in the state – unknown to an original inventor – that it will be later recombined.

Increasing original inventors' share of eventual returns by raising $\lambda_1(c_j, c_k)$ do not change their incentives to invent. Since the original inventor does not know about the future recombination which may create recombinant value ($K_{j\{jk\}}(0) = 0$) giving them a larger share of the returns from future recombination is pushing on a rope.

This example, while extreme, reveals the importance of entrepreneurial knowledge. An invention which will gain value from later being recombined will, more generally, not have adequate invention incentives if the first inventor does not know about the potential recom-

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But there is a reason to assign a claim to both inventors.

[11] wlog, we examine the case in which k invents first and j second. At the second stage, $\pi_{jS} = V(T_j, T_k)\lambda_2(c_k, c_j)1 - r_j$ This can be less than zero only if $\lambda_2(c_k, c_j) < r_j/V(T_j, T_k)$. That is, too small an appropriability for j, the second inventor, defeats the joint invention. On the other hand, the same sequence can fail at the first stage if $\pi_{kF} = V(T_j, T_k)\lambda_1(c_k, c_j)1 - r_k < 0$, i.e. if $\lambda_1(c_k, c_j) < r_k/V(T_j, T_k)$. The invention order (k, j) fails if either $\lambda_2(c_k, c_j) < r_j/V(T_j, T_k)$ or $\lambda_1(c_k, c_j) < r_k/V(T_j, T_k)$.

bination. Note that this effect does not depend on there being anything odd about the first inventor's knowledge of her own business or her own market. She can be perfectly rational, perfectly foresighted, understand all technical possibilities without regard to whether they involve a conceptual break through or not, etc., etc. The key assumption is one of decentralization, i.e. that she does not know about future technical possibilities in another business where her invention might be recombined.

This kind of scarce entrepreneurial knowledge raises the social return to innovation above the private return. Indeed, whenever we see recombination, it is reasonable to suspect that earlier entrepreneurial information about the then-future recombination was scarce. The private incentive of the original inventor to invent fell below what we now know, using ex post knowledge, was the social incentive. But this argument must be treated very carefully. The high "social return to innovation" of the first innovation can be calculated only by using all the information in the economy, not the information available to any inventor. Nor can conventional incentives (claims, market positions, etc.) raise the private return up to the social return.

Increasing V has no impact on equilibrium, and increasing λ_1 also has no impact on equilibrium, even though it is the first invention whose incentives fail. This extreme example suggests the multi-use market invent-around we discuss below. But first a more careful discussion, in less extreme circumstances, of the role of distributed entrepreneurial knowledge.

Two Invention Model with Distributed Knowledge

In this variant, following models of optimal patents, assume that there is variety in r_j, which is an i.i.d. random variable with distribution F on $0, \infty$. This will permit calculation of the probability of invention and as a result permit comparative statics in the "policy" variables. Finally, assume that only one partner, k, out of the continuum of potential inventions, is suitable for recombination with each j. This is a context in which it is natural to assume that potential inventors cannot necessarily find their innovation partners ex ante unless they have entrepreneurial knowledge.

Special case 2, limited entrepreneurial knowledge. Fixed V with $V(T_j) = V(T_k) = V_1 < V(T_{j,}T_k)/2 \equiv V_2/2$ (but only one specific k will work for each j.) Potential inventors do not know their innovation partners *ex ante* ($K_{j\{jk\}}(0) = 0$), but will recognize an innovation by their partners if it is marketed ($K_{j\{jk\}}(T_k) = 1$). Each potential inventor can also perfectly assess the value of a standalone invention ($K_{j\{j\}}(0) = 1$). Symmetry also suggests we write $\lambda_1(c_j) = \lambda_1$ and $\lambda_2(c_k, c_j)) = \lambda_2$.

Because the r are random variables, all four forms of equilibrium occur with positive probability. We can calculate the probability of each form of equilibrium simply.

Neither invented. $\pi_{jF} \leq 0 \quad \text{and} \quad \pi_{kF} \leq 0$ These are two independent events and each has the probability that $V(T_j) - r_j < 0$, i.e. $1 - F(V(\lambda_1(c_j)T_j))$. By symmetry of the V:

$\Pr(0, 0) = (1 - F(\lambda_1 V_1))^2$.

Both invented. Here there are two cases. If $\lambda_2 V_2 < \lambda_1 V_1$, it is never in the interest of a second inventor to follow. In this case, the probability that both are invented is just $F(\lambda_1 V_1)^2$. In the alternative case $\lambda_2 V_2 \geq \lambda_1 V_{1,}$ then both are invented if $\pi_{jS} > 0 \quad \text{and} \quad \pi_{kF} > 0 \quad \text{or} \quad \pi_{kS} > 0 \quad \text{and} \quad \pi_{jF} > 0$ Now the event $\pi_{jS} > 0 \quad \text{and} \quad \pi_{kF} > 0$ has probability $F(\lambda_1 V_1)(1 - F(\lambda_2 V_2))$ and the two events overlap by $F(\lambda_1 V_1)^2$, so we have

$\Pr(1, 1) = 2F(\lambda_1 V_1)(1 - F(\lambda_2 V_2)) - F(\lambda_1 V_1)^2$

The remaining probability goes to one potential inventor investing,

$\max[\pi_{jF}, \pi_{jS}] \leq 0 \quad \text{and} \quad \pi_{kF} > 0 \quad \text{or} \quad \max[\pi_{kF}, \pi_{kS}] \leq 0 \quad \text{and} \quad \pi_{jF} > 0$ whose probability can be obtained by subtraction. Since in later models we will care about the identity of an initial inventor, let us write out the probability that only j invents. This is $F(V(T_j)) \Pr(\min[V(T_{j,}T_k)\lambda_2, V(\lambda_1 T_k)] < r_j)$ which is $F(V(T_j))(1 - F(\min[V(T_{j,}T_k)\lambda_2, \lambda_1 V(T_k)])$

Comparative statics

More generally, even when we let both K and λ be arbitrary, we get the result that, the more important is low K as a source of poor returns to innovation, the weaker are increases in λ as a mechanism to overcome it.

Note that increasing the claims assigned to a first inventor that extends to the second inventor in this model (weakly)reduces λ_2 and thus has only (weakly) negative impacts on the rate of innovation in the economy. The reduction is only weakly negative, as it can reduce second-inventor activity to zero (and have thereafter a zero impact) once λ_2 is sufficiently large that $\lambda_2 V_2 < \lambda_1 V_1$.

$E[U] = \Pr(0,0) * 0 + \Pr(1,1)V_2 + (\Pr(0,1) + \Pr(1,0)V_1$

The essential feature of this example is that increasing the broad appropriability of original inventors can only have negative impacts.

Remarks

The novel idea in this section is that the invention and commercialization of a technology depends on entrepreneurial knowledge and creates market knowledge. This puts recombination in a new light. In a decentralized economy, the *ex ante* perception that a particular invention might later be recombined is entrepreneurial knowledge. Scarcity of entrepreneurial knowledge *ex ante*, like the more familiar problems of weak appropriability or scarce technical knowledge, limits incentives to innovate. Evaluating either the private or the social rate of return to invention using all of the decentralized knowledge that exists in the economy, would reveal the positive returns flowing from recombination. The problem in the case of scarce entrepreneurial knowledge is that no one knows enough to make the calculation.[12]

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[12] Hayek (1945) pp. 519-521: "The peculiar character of the problem of a rational economic order is determined precisely by the fact that the knowledge of the circumstances of which we must make use never exists in concentrated or integrated form, but solely as the dispersed bits of incomplete and frequently contradictory knowledge which all the separate individuals possess. The economic problem of society is thus not merely a problemof how to allocate "given" resources-if "given" is taken to mean given to a single mind which deliberately solves the problem set by these "data." It is rather a problem of how to secure the best use of resources known to any of the members of society, for ends whose relative importance only these individuals know. Or, to put it briefly, it is a problem of the utilization of knowledge not given to anyone in its totality."

Incentive Policy and the New Contractarianism

Just as the *ex post* perspective reveals the considerable social benefits to the spillouts from re-use, the *ex ante* perspective reveals the social costs associated with incentives for re-usable technical advance. Here there is an asymmetry between imitation as a problem (which lowers λ ex ante) and scarcity of entrepreneurial information as a problem (which lowers $K(0)$.) The problem of imitation can be solved, if imperfectly, by giving an original inventor a narrow right to exclude rivals. Scarce entrepreneurial information limits the effectiveness of such a right in creating incentives. Worse, not only is stronger appropriability not productive ex ante, if the rights given to original inventors are broad enough to encompass unforeseen recombination, they are counterproductive. They limit the incentives of later inventors – who work in a better knowledge environment.

After the first stage of a recombination that involves market knowledge creation, the knowledge state of the economy changes. That is, the market knowledge $K(T_j)$ is better than $K(0)$ as an indicator to potential complementors outside the j sector of what could be invented in j. If there is recombination caused by this increase in market knowledge, i.e., if a second, complementary invention occurs as a result of the increase, that is not, typically, a reason to favor appropriability for original inventors but instead a reason to favor openness.

Knowledge Policy

One could think about limited entrepreneurial knowledge – in the model, a small $K(0)$ – from at least two perspectives. One very useful normative perspective examines private and public actions to improve $K(0)$ Costs of storing, retrieving and communicating knowledge might be lowered, reducing the possibility that distributed knowledge is a bottleneck. [cites] The available stock of knowledge in the economy might be partially codified into science, and access costs to that science could be lowered. This creates a widespread knowledge asset, reducing the degree to which technical knowledge is local. [cites] Of course, as the total volume of knowledge rises, the costs of information processing can make this less effective.

(See the discussion of Weitzman and Jones, above). Specialized structures, known in the literature as "absorptive capacity," may be needed at the firm level to lower the costs of information access. Firms may learn how to undertake "recombinant search" to somewhat lower the costs of finding outside information. To the extent that the critical information is about potential customers (as when the potential inventor of an intermediate good or producer's durable considers whether any potential customers will find a way to use it in their productive process) marketing research, discussions with "lead customers" and the like are all potential solutions. [cites]

It is worth pointing out that all of these normative ideas, however valuable within their scope, may be of limited relevance to the economic problem of an initial invention which later be re-used. Making knowledge that already exists easy to retrieve broadly is a good thing, but on its face it refers to making $K(T)$ large once T is known, rather than increasing $K(0)$. Second, the scope of such strategies is limited to knowledge which is easy to codify and store. As we move from science to engineering to production of goods to production of services to demand for goods to demand for services to demand for fun, it may grow more and more difficult to codify knowledge and make it retrievable to everyone, everywhere. Third, there are excellent reasons, related to the day-to-day functioning of the economy, why knowledge is decentralized, so it may simply not be cost-effective to have everyone know everyone else's business well enough to know exactly what everyone else might create. In short, the shortage of entrepreneurial knowledge in the economy may be a social cost.

Indeed, I shall argue in my historical section below that we should understand the entrepreneurial-knowledge shortfalls that bottlenecked some very important late 20th century GPTs were, in fact, social costs. My argument there is grounded in specific historical detail but it has two central lines. First, simply stating the information bottleneck precisely is very helpful. Knowing who did not know what can let us consider the possibility of an alternative economy in which someone had entrepreneurial knowledge ex ante of the key overlaps That alternative economy is extremely centralized or at least densely populated with (influential!)

polymaths. Second, some of the relevant inventions fulfilled long-perceived needs and thus were addressed both by efforts to create

Not (Just) Science

The optimality of a low share for an early inventor has nothing to do with science per se, though the argument clearly applies to (pre-commercial) science. The essential feature of the argument is about cabining scope into the known – you could have (very) narrow commercial patents and open followon and it would work. This point is related to my examples, which have serious Rosenbergian nonlinearity (and some technical convergence.) It is important to recognize that K can be off not just because don't know what's right but because do know something that turns out to be wrong.

The event of recombination need not be a "black swan" from a social perspective. What is critical is not that the event be rare, but that the knowledge needed to forecast the event (or to forecast it accurately) be distributed.

I have emphasized the possibility of entirely symmetric imperfect knowledge – a scarcity of entrepreneurial knowledge – because the point does not appear in the literature on recombination or other kinds of re-use and appears to be as relevant to a market economy as points which have received treatment at great length. I emphasize the case in which scarcity of entrepreneurial knowledge is a social cost. I now turn to the founding of GPTs, another important problem when entrepreneurial knowledge is scarce.

The Founding of GPTs with Imperfect Knowledge

There is a natural tendency to think of GPTs in a hierarchical way. Someone invents a GPT, offers it to potential users, and induces applications sector investment in complements. In this section, I call such a path to the invention of an entire GPT cluster a "planned initiative" and point out that a successful planned initiative turns on the entrepreneurial knowledge of the firm designing the practical GPT product.

A planned initiative is not the only path to invention of a GPT. Innovation in a number of important GPTs has followed a "circuitous route." I define a circuitous route as having three characteristics: (1) Inversion, (2) Decentralization and (3) Acceleration. In this section, I show a model which makes definition of all three elements precise. (1) Inversion: The first invention leading to creation of a market in the GPT has a narrow and specific purpose serving a moderately valuable use. The economic motivation of the original invention does not include either generality of purpose or more valuable uses than its narrow and specific purpose. (The word "economic" here is important. Many inventors hope and anticipate that their invention will be generally useful, and it is important for causal arguments that this does not always lead to investment in their invention.) (2) Decentralization: A series of innovations, arising from a number of sources, leads to the successful exploitation of the *ex post* more valuable uses. Key steps in this sequence of innovations are not coordinated *ex ante*; instead, early innovations create knowledge about markets that informs later innovators. (3) Acceleration: Once it is known that the "GPT" is general, the positive feedback associated with social increasing returns to scale raise the returns to invention of improvements to the GPT and co-invention of applications.

In this section, I show that the scarcity of entrepreneurial knowledge can easily explain a circuitous route. The key point is the scarcity of entrepreneurial knowledge is resolved by inversion.

The final point of this section is that a circuitous route is a market work-around to the problem posed in the last section. Suppose scarcity of entrepreneurial knowledge blocks coordinated invention of technologies j and k in circumstances where the social value of inventing both is very high. Now suppose that j has another potential partner, k', and that the joint social value of inventing both j and k' is positive, if not very high. Excellent entrepreneurial knowledge that links j and k' can lead to an inversion (j and k' are invented first.) If the invention of j and k' creates market knowledge that permits an inventor interested in j to see the value of a j, k,match, decentralization follows. If k is very valuable, or if there are a number of k's that see the value of a match to j (or to an improved version, j') an acceleration follows.

The essential point of that example is the generality of j. From an ex post perspective, we can see that it is a GPT. Ex ante, however, the scarcity of entrepreneurial knowledge may have meant that potential inventors of j did not know that there would be complementary invention. Or, equivalently from an economic perspective, potential inventors may have had some vague idea that there would be complementary invention, but not known specifically enough to warrant investment what features, pricing, or marketing plan would work to draw out the complements.

There are a number of similarities between a GPT and a technology that will be later recombined, as analyzed in the previous section. There is also one critical distinction. For our purposes, the most important similarity is multiple inventors. It is essential to a GPT that there are separate inventors in a number of distinct technical areas, the various applications sectors and the GPT itself. Thus the creation of a new GPT has at least the possibility of scarce entrepreneurial knowledge. The most important difference is that a GPT (again by its very nature) has technology has many potential AS partners: if one of these, even the most valuable of these, is blocked by a scarcity of entrepreneurial knowledge, others need not be.

It is thus worth considering the case, historically important as we shall see, in which a scarcity of entrepreneurial knowledge creates a bottleneck to the invention of a GPT and its most valuable application. This situation is not nearly as grim in the case of a GPT as one might imagine. There can be a market work-around the bottleneck. The workaround follows a circuitous route, beginning with a less-valuable application in which entrepreneurial knowledge is not so scarce, and continuing through decentralization to acceleration. As we shall see, openness is important here by permitting decentralization as part of a circuitous route. In this section, we examine the conditions for emergence of a circuitous route as a market work-around.

A call this a *market* work around to contrast it with much *antimarket* thinking about the origins of platforms and of GPT industries. [cites] Planning and contracting play little role in this structure. .

At some risk of losing the point that ex ante it is not obvious what is, in fact, generally useful, in this section I am going to label with a g those technologies which, examined using all the knowledge of all the potential inventors in the economy, are general purpose. Similarly I will label complementary technologies a, though it is essential to the argument that scarcity of entrepreneurial knowledge can leave, ex ante, many businessmen ignorant of the fact that they work in a potential application sector of an as yet undiscovered GPT.

In this section, there is also a bit more structure on the payoffs. Every productive use requires an "A" (applications) technology investment and is thus contingent upon technical and market knowledge of sector A. In some circumstances, productive use may also take advantage of a generally useful technology, G.

After the last investment that bears on the use of technologies g and a in sector A is made, value V_{ag} is created. The last inventor – either a or g – will invent if (1) her share of this value is large enough to cover her costs and (2) she knows of the opportunity. We simplify everything about appropriability by assigning her a share of the value that depends on the bargaining power, as in the earlier model.

Basic Model and Notation for GPT

As in the earlier sections, we need a list of potential combinations of technical advances (i.e. the technologies which can be produced by all subsets of potential inventors) which is called T. $T = \varnothing, T_1, ...T_j, (T_1, T_2), ...(T_{J-1}T_J), (T_1, T_2, T_3)...$ Associated with each member of T is a value created.

In this section, however we restrict the value creation to involve specific pairs. The value created in an applications sector a if both a GPT g is invented and an application is invented is V_{ga}, and the special case of no GPT is V_{0a}. If more than one g has been invented, call them $\{h\}$, assume $V_{g\{h\}a}$ $=\max_{\{h\}} V_{ha}$. This assumption permits the best characteristics for a particular application to be invented, not necessarily first. Recall that while we know that is a g and what is an a, ex ante inventors do not know this.

Claims on the return to invention, λ, follow the notation used above. Thus, for example, if a series of g has been invented and a has been invented after the k'th g, then the list of claims is $c_H = c_{h_1}, c_{h_2}, ... c_{h_k}, c_a, ...$ and a's level of appropriability is the $k+1$th element of $\lambda(c_H)$. As above, we denote this as $\lambda^a(c_H)$ Then a's payoff is $\lambda^a(c_H)V_{g\{h\}a}$. This notation also makes it easy to write the payoff to a particular g from this application in the sequence as $\lambda^g(c_H)V_{g\{h\}a}$. If there is more than one application, the total return to a g will be a sum.

Ex ante invention, a does not necessarily know if any g will invent but has some entrepreneurial knowledge, $K_a(0)$. This is updated by history T. As above, $K_a(0)$ refers to all the states that a cares about, even ones she does not know about. The calculation is symmetrical for g, again using the notation from above.

No Invention in Equilibrium

No invention is an equilibrium if, evaluating all of the knowledge states at $K(0)$, no potential inventor has an incentive to invent. For a g this is

$$\sum_a V_{ga}\lambda_1(C)K_{ga}(0) - r_g < 0 \tag{3}$$

This condition states that no potential GPT inventor has an incentive to invent as a planned initiative, anticipating follow-ons by a. . That is one of the two ways to start the process.

For an a, the comparable condition is

$$\max_g V_{ga}\lambda_1(C)K_{ag}(0) - r_a < 0 \tag{4}$$

A key difference between the g and a conditions is that the a seeks the best-fit g it knows of while a g seeks broad coverage. It is also the natural interpretation of $K_{ag}(0)$ (in the case where an a moves first) that the a has made some preliminary approaches to a g. In that case, we might consider the closely related model in which there is a ga contract by which a commissions g to make a component (a component we, if not necessarily a, know is general purpose.)

If we now consider the comparative statics of the "no invention" state, we can see that almost all of them are the same as the comparative statics of the model of recombination when j, k are a potential complementary pair of inventors. Indeed, if every g has only one a, this is the same model as that one.

One new comparative static result arises because of the potential match of a g to more than one a. Increase the number of a sectors for which $V_{ga} > r_a$. Call the additional a sector inventors a' for clarity. Endow a' with no worse information or appropriability than the existing sectors, a. That is $K_{ag}(T) \leq K_{a'g}(T)$ and similarly for the claims. Finally, and this is the one part of this comparative static which is not exactly a replication[13], endow g with as good information about the additional sectors as about the original sectors: $K_{ga}(T) \leq K_{ga'}(T)$. Then it follows directly that removing a' can create a situation in which (4) or (3) holds but adding a' cannot.

This result is obvious, as the related result in which we make (again following the earlier model) r and K random variables, and replicate applications sectors by adding an a' drawn from the same (or better) distribution as existing sectors. In this case, it is clearly true that the probability that (4) and (3) both hold falls if we add an a'. This is the model which can have inversion with positive probability. When the event $\sum_a V_{ga}\lambda_1(C)K_{ga}(0) - r_g > 0$ occurs for a sector with particularly high $K_{ga}(0)$ but not particularly V_{ga}, and all other instances of (4) and (3) hold, there is an inversion.

Thus the possibility of an inversion requires incomplete entrepreneurial information

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[13] It is not a replication as it endows a single agent with wider knowledge of the economy. The result asserted in text is still true if the g has less information about each potential a but the aggregate information does not decrease. In the case of symmetric a, this would be $\sum K_{ag}(T)$ does not decrease as we add a'.

but is not a particularly surprising result once incomplete entrepreneurial information is introduced. To get inversion as a high probability event, however, we need some force which creates a negative correlation in the cross section of a sectors between V_{ga} and $K_{ga}(0)$. If high value applications sectors are the ones, for example, which need to experiment to take advantage of a new g capability, that would imply such a negative correlation and thus increase the probability of inversion.

Special Case of Technological Convergence/Inversion

Suppose that for each a, there are two potential ways to create new value. One is a compromise, specific to the sector and involving invention of T_a and $T_{\gamma(a)}$. The other is an efficient general to all sectors and involves invention of T_a and T_G. To capture "compromise" and "efficient" assume that $V_{Ga} > V_{\gamma(a)a} > V_{\gamma(b)a} = 0$ if $b \neq a$. However, $r_G > r_{\gamma(a)}$ for all a, although (bounds to make it efficient!) Will the equilibrium hold up at no invention? Will it ultimately find the efficient GPT? We examine the scarcity of entrepreneurial knowledge by considering the very simple case in which $\Pr[E_{ga}(0)|xxtrue] = \rho = \Pr[E_{ag}(0) = 0|xxtrue]$.

The condition for the GPT not to be invented on spec is:

$\sum_a V_{Ga}\lambda_1(C_{Ga})E_{Ga}(0) - r_G < 0$

and, taking the expected value, we see the relationship between the perfect-entrepreneurial information and imperfect-entrepreneurial information payoffs is

$$\sum_{A(G)} V_{Ga}\lambda_1(C_{Ga}) - r_G > \rho \sum_{A(G)} V_{Ga}\lambda_1(C_{Ga}) - r_G < 0 \tag{5}$$

Note that this condition has the advantages and the disadvantages of scale. The advantage of widespread applicability and large scale is that the fixed cost r_G is spread over many AS. The corresponding disadvantage arises when entrepreneurial information is scarce, for then potential GPT inventors may not know of the specific needs of their potential customers. In the case where ρ is small enough that the RHS of 5 is negative,

$(\rho < r_G / \sum_{A(G)} V_{Ga} \lambda_1(C_{Ga}))$ then the absence of entrepreneurial information about broad opportunities makes invention of a GPT on spec uneconomic.

For an a to invent using $\gamma(a)$, the comparable condition for no invention is

$$V_{\gamma(a)a} E_{a\gamma(a)}(0) - r_a - r_{\gamma(a)} < 0 \tag{6}$$

If the costs $r_{\gamma(a)}$ are so large that $V_{\gamma(a)a} - r_a - r_{\gamma(a)} > 0$ can never be satisfied, that is the end of the story. If, however, there is a positive probability in the cost distribution that this is satisfied, call it $\Pr_r[V_{\gamma(a)a} - r_a - r_{\gamma(a)} > 0] = \Psi$. Now the fraction of AS which invent will be determined by the availability of entrepreneurial knowledge plus the incidence of these one-off costs. That is, the fraction of the time 6 will fail [?????] is $\rho\Psi$.

Thus, with our assumptions, the first stage of equilibrium under $\rho < r_G / \sum_{A(G)} V_{Ga} \lambda_1(C_{Ga})$ involves invention by AS using the local (γ) technology $\rho\Psi$. This first stage has elements of an inversion. To be sure, market equilibrium selects some higher-value applications, since $V_{\gamma(a)a} - r_a - r_{\gamma(a)} > 0$ for each first-stage invention. However, only those applications with entrepreneurial knowledge invent at this stage, and they need not be the high-value ones.

Will there be an acceleration? We assume that every GPT's entrepreneurial knowledge is updated to include market knowledge of AS that have already invented. Now the condition for G not to invent is

$$\rho \sum_{A(G)-A1} V_{Ga} \lambda_1(C_{Ga}) + \sum_{A1} V_{Ga} \lambda_2(C_{\gamma aG}) - r_G < 0 \tag{7}$$

If the nature of open systems means that γ has no claim (i.e., that a first-round a has no claim on later inventions, now the condition for no second-round GPT entrepreneurship is

$(\rho + \rho\Psi) \sum_{A(G)} V_{Ga} \lambda_1(C_{Ga}) - r_G < 0$

If there are entrepreneurial-information spillouts across AS at rate ε, the success of $\rho\Psi$ percent of AS leads to a further informing of $\rho\Psi\varepsilon(1 - \rho\Psi)$, of which in turn Ψ will succeed

... and spill out .. to apps which will succeed ... and spill out. If there are open systems so that none of these spillouts are limited by owing royalties to earlier applications (or which need strategic approval of earlier applications) then the total number of "local" applications is $\rho(1-\rho)\Psi\varepsilon/(1-\Psi\varepsilon)=\theta$

Then the condition for no after-amateur GPT entrepreneurship is

$(\rho+\theta)\sum_{A(G)} V_{Ga}\lambda_1(C_{Ga})-r_G<0$

This can be substantially larger than ρ depending on the success rate of "local" applications and the spillout rate.

Remarks

In this section I have constructed a model with the simplest structure that explains Inversion, one built around limited entrepreneurial knowledge. Inversion is an odd enough phenomenon that it calls for adding something to the model. An added benefit is that the model predicts Decentralization and Acceleration. It explains why, in the case of a GPT, a market work-around is available to deal with bottlenecks caused by entrepreneurial knowledge scarcity. How important these phenomena are can only be investigated by looking at cases where the scarcity of entrepreneurial knowledge mattered for the rate and direction of technical change.

Historical Examples

I study the invention of information technology and the co-invention of applications for three related reasons. IT and its applications, particularly its applications in the automation of white collar work (WCA), are among the most important contemporary technologies. There are a number of rich descriptive literatures on IT, and these permit researching the relevant questions. Not least, the industry is particularly well suited to studies of knowledge because its industrial organization leads to frequent public communications.

That last point is critical to the success of historical methods as a way to learn what potential inventors did not know. The sellers of the GPT itself – the computers themselves, essential infrastructure software (operating systems and the like, programmer tools) and networking components – do not do all of the invention. There is a great deal of invention in applications sectors – in firms which undertake WCA, and in specialized applications sectors which supply to them – as well. Happily for research, there is a great deal of public communication between GPT and AS about technical directions. A number of sources have also brought out once-private knowledge later on. The retrospective view is also critical to my research approach. *Ex post*, we can observe which GPTs are usefully applied where. We can then ask whether, at *ex ante* or interim stages, entrepreneurial knowledge of those overlaps between technical opportunity and growth needs guided R&D.

I consider the three most important computer GPT clusters for WCA to date. These are (1) mainframe computing (and its current replacement, server computing), (2) personal computing, and (3) the widespread use of the Internet and the WWW. These three GPT clusters have included a wide range of WCA applications in (1) business data processing, (2) personal productivity computing, and (3) electronic commerce, communication, and content dissemination. The third one recombined the first two (and a number of other technologies) and its applications have considerably expanded the demand for them. The striking thing about all three of these GPT clusters is that each began with an Inversion, following, at least for a while, a Circuitous Route. In addition to asking what it was that led to this interesting outcome, I compare these three GPTs to two other inventions, in which entrepreneurial knowledge was far less scarce and a Planned Initiative succeeded.

Entrepreneurial Knowledge Scarcity and Market Work-Arounds

Because of a scarcity of entrepreneurial knowledge linking an important technology to its most valuable use, one of the 20th century's most valuable GPTs, mainframe computing in business data processing, was invented in an inversion. The key shortage of entrepreneurial knowledge arose in a specific locus. It was difficult to see, *ex ante,* the overlaps between what was technically feasible and the areas of greatest demand need. Those overlaps became more visible at an interim stage, after the invention of general purpose computers to meet significant, but lesser, demand needs. Close historical investigation of this inversion reveals a number of interesting points.

After a century of increasingly detailed and sophisticated work with electricity, much of the engineering knowledge that would permit a tube-based electronic computer was widespread in the economy by the 1930s. At the same time, the economies of the rich countries faced a growth bottleneck in service industries and in the white-collar functions of all industries. The bottleneck arose because automation of physical processes and of blue-collar work in many industries, e.g. in manufacturing, was very successful but was, over the next half century or so, destined to be subject to diminishing returns. One thing clearly needed for further growth was technical progress in white-collar automation (WCA).

Today, we all know that one group of uses of electronic computing was going to be business data processing for automation and product quality improvement in service industries and for the white collar functions of all industries. Ex post it is obvious that this is an overlap between technological opportunity and demand need. That same point was not obvious at the end of the second world war. To be specific, what was not obvious was the entrepreneurial knowledge of the overlap. There was a great deal of excitement about the prospects for computers, largely among scientists and engineers interested in *calculation.* There were also successful firms engaged in business data processing, such as IBM. Like its competitors, IBM was investing overwhelmingly in research and development of mechanical and electromechanical technologies, not in digital computers.[14]

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[14] IBM did have some research projects with computer-like features in its labs. These projects did not, however, go anywhere. Even after much better computers appeared from outside the firm, however, IBM's management thought that their commercial application would be very narrow. An example was selling to the census bureau, since it had to do quite large calculations. None of this should be taken to mean that IBM (or a similarly situated firm) would never have invented something like the computer. A large technilcal opportunity / demand need overlap can be filled in many ways, possibly potentially perhaps even including that one.

No single agent in a position to act on it had knowledge of the key role to be played for computing in the second half of the 20th century. When I say the knowledge did not exist, I do not mean that no one had ever thought that something like the computer would be useful in something like business data processing. Almost all ideas of any importance have been anticipated somewhere. Historians of science and technology as bodies of ideas often focus on those anticipations. But that is not the focus relevant to the creation of working markets in a new technology that fuel economic growth.

What I mean instead is that the idea inventing computing as a backbone technology in business data processing had never been specific enough to earn serious commitment of resources to a program of research, The financial contributions needed to invent the electronic computer as we now know it did not come from those interested in business data processing. Instead, they came from people who could see the value of literal computation, military people with complex engineering or scientific calculations in mind. Only after the invention of the computer as calculating machine did business data processing firm, most successfully IBM, recombine it with a number of other inventions to create mainframe computing.

To make effective use of a GPT involves both invention of the GPT and co-invention of the application.[15] Further, the invention and co-invention need to be congruent, i.e., work together to create value serving a specific demand. No one who understood the demand needs of business data processing was involved in the design of electronic computers or with important architectural ideas such as the stored-program computer. They lacked the relevant entrepreneurial knowledge. Instead, those (and many other very important computer technologies) were invented to support scientific and engineering calculations, frequently supported by military funding. Very important examples include the work, funded by the Army, of Eckert and Mauchly at Penn, and the work of physicists and mathematicians recruited to work on atomic weapons projects, notably John von Neumann.

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[15] Similarly, recombinant technical change requires both invention of the original technology and later invention of the recombinant application. In the case of recombination, we already assume that the invention and co-invention take place in two steps. My fundamental argument is that the second step is easier given the first.

The sense in which the scientists and engineers invented a GPT was that they invented a *tool* that they could use in scientific and engineering calculations. This tool turned out to be suitable for recombination outside the range of science and engineering. That recombination led to a very large spillover from the scientific sector to the rest of the economy (to which we shall turn in a moment) but the spillover did not flow through application of the science itself. The essential role played by the scientific-ness of the original inventors in the spillover process was not the new scientific knowledge (though there were also spillouts of some of the knowledge, e.g. though peaceful nuclear power.) Instead, there were two essential roles. The first was that the tool inventions were designed to be general, in this case, general calculating engines. This is not the same as the assertion that the scientists foresaw all the range of useful calculations that might be made. The second essential role of science here was the openness with which the tool was delivered to the rest of the economy, including other scientific and engineering disciplines, but especially to unrelated commercial application.[16] Making a general tool and making it available to others who might use if for purposes you yourself do no know is a perfectly ordinary scientific behavior. As a result of the generality and openness, the commercial business data processing industry drew on government-funded science and engineering. The spillout was the recombination of an input into science, however, not "the commercialization of science" as often understood.

My point is not that it is always that way. Indeed, we could take another very important example of the commercialization of science that had its impact right afterward in the same industry. The discovery and associated inventions of the semiconductor effect, the transistor, and the integrated circuit were an extremely important spillout from science to the computer industry, very much the commercialization of science. My point is much more that the organizational structures and values that supported openness, generality, and disclosure, which exist in scientific communities, to be sure, but also in some other invention communities, can form very important parts of a market work-around when the linear path

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[16] It was thought for a time that Eckert and Mauchly had a patent as a result of the ENIAC, but this turned out to be incorrect.

is blocked by lack of entrepreneurial knowledge.

The second important point here is what was obvious and what was non-obvious about the various scientific and engineering calculations which motivated creation of computers as a tool. The point is absolutely not that the science and engineering itself was simple or obvious. For example, the calculations needed to design the H-Bomb involved understanding some of the deepest mathematics and physics ever conceived, and in that regard were hideously complex. What was ex ante obvious was the relationship of those calculations to computation. Once the mathematics and science were understood, the calculations were calculations. Their *relationship* to a machine which could do calculations was, unlike the calculations themselves, not complex. That relationship is *entrepreneurial knowledge.* One potential AS, scientific computing, had very good entrepreneurial knowledge, particularly in contrast to the inadequate entrepreneurial knowledge associated with

Scientists and engineers were also well set up to understand the technical requirements of an electronic calculating machine itself. They could see, once the problem of creating a machine to undertake calculations was set, paths to making such a machine. This was an example of particularly good entrepreneurial knowledge about the value of a new technology, electronic computers,

This is generally true of scientific and engineering calculations. The user is a scientist or engineer and understands his value-creating task in terms of specific quantitative calculations. While implementing those calculations in an algorithm may be complex, the relationship between that implementation and a calculation is direct.[17]

In contrast, most managerial applications of business data processing have a very complex relationship between the business logic of the application and the technical capabilities of computer hardware and software. The simplest are accounting and finance and even they have a more complex interface with calculation than do typical scientific or engineering

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[17] It is, of course, not true of scientific and engineering tools in general. Those are often built in interdisciplinary teams where one knows the purpose and the other the methods. Entrrepreneurial knowledge is needed for that.

calculations. Not everything that we now recognize as suitable for "computation" was, in 1950, see by anyone in the economy as involving much calculation. It is important to understand that even those who were about to understand the technical possibility / demand need overlap most clearly did not understand it at an early stage. Think, for example, of the early assessment by the head of IBM that demand for computers would be limited because only census bureaus and similar agencies would need to do enough arithmetic to make effective use of a computer.

It is a mistake, a very common mistake, to think that the only entrepreneurial information problem at an early stage is a shortage of "vision" on the part of "visionaries," i.e., individuals or firms who foresee the future. This misses a central important point about entrepreneurial knowledge. Market economies can, with the help of enough openness, achieve breakthroughs that were unforeseeable. Of course, those breakthroughs come later than they would have if there had been a single individual with all the knowledge of both technical possibility and demand needs. The distributed state of such knowledge, and the problems associated with turning it into knowledge held by a single decisionmaker delay the invention; they are a social cost.

We shall see that difficulties like this in the uses of computers persisted for (at least) half a century. The essential point is not that value and technology is each complex but that it is complex to know – with regard not to an ideal technology but to the one which can reasonably be invented – where, exactly, the overlap between the feasible and the desirable lies.

Once the computer had been invented and was being applied to an every widening circle of computations, the knowledge state of the economy changed. Many people could now see the possibility of the general purpose computer as a business tool, at least in applications which were obviously computational, such as accounting, finance, and some operations management tasks like inventory control. To be sure, the electronic computer would have to overcome serious disadvantages relative to electromechanical devices, such as low reliability.

That, however, could be conceptualized as a technical/engineering problem. A wide number of firms, with an extremely wide range of knowledge bases and capabilities, entered a race be the leading computer vendor in business data processing. IBM, though its technical knowledge base lay mechanical and electromechanical business data processing, won this race.[18] IBM took advantage of newly public knowledge about computers, its own existing knowledge about the needs of business data processing, and undertook significant recombination.

There are two key points here is how the open availability of technical knowledge about computers was important. The first is the obvious one that a system which created technical knowledge and opened it to a firm, IBM, which already understood business data processing on an earlier technological basis, created entrepreneurial knowledge where none had been before.[19] Less obvious but equally important is that the openness created a large number of recombinatory experiments in combination with one another. No one knew exactly what a business data processing computer looked like even after they saw a successful scientific computer. The competitive experimentation race to establish a successful business data processing business around the mainframe computer worked very well in such a knowledge-challenged environment.

The founding of the computer industry, a very valuable GPT that supports the important cluster of applications known as business data processing, is an important example of an inversion.

A planned initiative succeeds

An inversion is an inherently transitory state. It is a market mechanism by which the economy works around a shortfall of entrepreneurial knowledge. Once an inversion

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[18] See Bresnahan-Malerba on the nature of this competition and, especially, on the point that IBM formed an organization designed to link knowledge of customers' business needs to knowledge of what was technically feasible in computing.

[19] Some "entrepreneurship" scholars may fault my (and Hayek's) usage here, but I think it is apt. IBM was the leading firm in an existing technology for business data processing, but walked away from its existing capabilities to create new ones. Whatever you make of the claim that "elephants can dance" about IBM in the last 15 years or so, it was highly true of the firm in the 1950s.

is completed, the newly created information about technical progress may lead, through decentralization, to recombinant invention by distinct inventors than those who participated in the original inversion. Those new inventions can lead to an acceleration, completing the circuitous route to the founding of a market.

In the case of business data processing there was still a great deal of invention to be undertaken in computers themselves and in their commercial applications to build a complete GPT cluster. What is quite interesting about those next steps is that they took a radically different form: IBM undertook a planned initiative to construct a GPT cluster centered on the mainframe computer and induced customers, primarily large firms, to create applications. More precisely, they took the form of a competitive race among a number of distinct business data processing firms which ended with an IBM standard.

In many ways, that occurred because IBM went to work to create the general purpose components that could be used by its corporate customers to build applications. IBM also built a very good computer design and engineering technical capability, though IBM was rarely the technical leader in computers, narrowly understood. Yet IBM offered a complete set of complementary general-purpose inputs, including hardware, software, storage, and other peripherals which reflected its knowledge of the kind of problems its customers were trying to solve. Further, IBM put in place an organizational support system which let its customers lower the risks of undertaking experiments in the applications of computers. The creation of the IBM mainframe standard was an example of how a planned initiative can build a GPT cluster. To underscore the key point here, once IBM understood the technical prospects for electronic computing reasonably well, that single firm had the entrepreneurial knowledge to undertake a planned initiative. It combined pre-existing knowledge of its customers' needs with new, generally available knowledge about what was technically feasible.

The key difference between the early Eckert-Mauchly (or von Neumann) stage of invention and the later IBM (and competitors) stage of invention is entrepreneurial knowledge. A scarcity of entrepreneurial knowledge located the first stage, not in the very valuable sector of business data processing, but in the still valuable but significantly less so sector of scientific and technical computing.[20] The success of that first stage at creating a general purpose tool changed the information state of the economy. In the new state, sufficient entrepreneurial knowledge existed to support planned initiatives to create a whole new industry.

Dauer im Wechsel

The first IBM mainframes and associated complementary general purpose components, while impressive enough to win the competitive race, were extremely primitive and unreliable by modern standards. They were also extremely slow. Scholars of technical progress in computing spend a good deal of time measuring the increase in speed. Increases in speed, like increases in reliability, formed an important part of the rate of technical progress in computing, and it would be foolish not to think of them as an enormous technical accomplishment. Equally important, however, was the direction of technical progress in computing, which turned computers from primitive calculators (eventually) into extremely sophisticated tools which literally perform the production process in a number of functions which were previously white collar work and, in some service industries, much if not all of the production

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One of the more striking things about business data processing and computing is that the problem of scarce entrepreneurial knowledge has never gone away. The best direction for technical change in the general purpose components at each stage depends on new applications that could be developed. The key entrepreneurial knowledge involves seeing the overlap between the technical capabilities that might be added to the general components and the new value which might be created by the invention of new applications.

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[20] At this stage it is perhaps useful to reiterate what V means in this paper. The judgment here is not about the ultimate social value of business data processing vs scientific calculation. Instead, it is the area under the demand curve for BDP vs. scientific, engineering, and other technical calculations (which takes the budget for science as given.) Whatever the importance of science to technology, it had significantly less willingness to pay for computers than did commerce over the second half of the 20th century.

In the long era of IBM's successful dominance, the solution to this problem had a number of interesting elements.

First, corporations began to experiment with the construction of new business data processing systems. As computers and general purpose complements improved, the range of experiments expanded into new territory. Much cutting-edge computer systems designs went badly (and much still does.) Successful experiments, and the entrepreneurial knowledge that arose from failed experiments, created a very large demand for computer systems. The business applications of computers were (and still are) a very difficult area for invention. A system of putting ever changing (often improving) GPT components out into the market and thereby enabling AS experiments permitted the discovery of many areas of overlap between the technically feasible and the valuable.

Second, IBM (wisely) built itself into an organization that could, among other tasks, create new entrepreneurial knowledge. IBM's field sales force was empowered to learn as much as could be learned about applications sectors from customers, and given considerable internal power, including having influence on the direction of technical change. This was a mixed success. It remained hard to foresee what technical change should be undertaken to support new kinds of applications, and it was often IBM's competitors, not the dominant firm itself, which first introduced what would be valuable improvements in computers. Those improvements became important to economic growth only if IBM imitated them, often with a lag. However, once experiments had succeeded at some customers and a desirable direction of technical change was known, IBM was very effective at pursuing it. Oh, what a wonderful world is debottlenecking! As the computer departments of customers began to report bottlenecks in computer systems design, IBM gave them fundamental improvements in programmer tools, such as the database management system

Perhaps the most important solution to the problem of scarce knowledge about applications/technology overlap was IBM's invention of the closed, modular platform. This invention reduced the risk of customer experimentation dramatically. If a customer discovered that a particular business application worked, but that it required a larger or smaller computer, larger or smaller data storage, etc., they could move to those components without losing their initial investment in invention. This supported one of the most important forms of experimentation in business data processing, the construction of a complex high value system on top of a simple system. A customer might build an accounts receivable system that just kept track of who owed what, and then build a complex decision-support system on top of it to guide the extension of trade credit. If the trade credit system worked, IBM could offer the larger computers and data storage, etc., needed to run it in a modular fashion.

In short, the mainframe computer industry succeeded, for a long time, in providing a series of expensive support systems for AS experimentation and feedback from those experiments into the direction of the dominant GPT.

No one-firm-dominated system can do that forever, and there was a difficult transition out of the IBM mainframe computer era into the current "server" era. I do not treat that transition in detail here, though Shane Greenstein and I have argued (cite) that its information needs were daunting and that the relevant information was highly dispersed.[21]

It is worth pointing out the contrast to another GPT cluster in the computing industry which did not supply business data processing customers in the IBM mainframe era, but instead supplied technical, scientific, and engineering customers. This "minicomputer" industry needed far less organizational infrastructure to support invention by its customers. Its customers were primarily technical people, with technical problems to solve. Thus the minicomputer industry did not need elaborate structures to create entrepreneurial knowledge. The relative scarcity and importance of entrepreneurial knowledge in WCA explains much of the difference of firm and industry structure between the mainframe and minicomputer segments.[22]

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[21] Shane & I Bresnahan and Greenstein (1996) concluded from our empirical analysis that the most valuable computer applications were also the most difficult to invent given a new computer technology. We also concluded that technical progress in computing and technical progress in the uses of computing are very different bodies of knowledge.

[22] I am grateful to Shane Greenstein and to Franco Malerba in this regard; without our collaborations I would never have come to understand this.

The creation of the business data processing industry carries the first two points of the paper. Information – in this case the information about a supply / demand match – can be more important than value in determining invention ex ante. We shall see that the most obvious calculation shows that information in this sense and value in the obvious economic sense must be, on average, coequal in determining invention ex ante.

Second, there are certain forms of information problem which are much more easily solved ex post invention of a GPT or a recombinable technology. Electronic business data processing was much easier to invent post the invention of the computer than it had been beforehand. To be precise about it, inventing electronic business data processing involved seeing overlaps between technical feasibility – with some effort, the electronic computer and certain key business software could be invented – and demand. This form of more visible overlap ex post is more important when demand stands for, as it does in this case, a very important growth pole.

There is another lesson. Computing as calculation has persisted in parallel with computing as business data processing until today – that is the essence of a GPT. And society would have made a positive economic return on computing (counting the economic return to weaponry without the externality of war or deterring war) if all it had ever done was scientific and engineering calculations for military, manufacturing, scientific, and engineering purposes.

This example leads to the second point of the paper. When information is partially blocked, the timing of invention is determined by the incentives and information in the unblocked directions. The rate of technical change for the aggregate is determined by the incentive to invent in a particular, visible, direction.

Examples of Successful E

iPhone..closely follows the logic of the IBM mainframe. A single firm has the relevant entrepreneurial knowledge. The path to invention is still roundabout, but not

Invention of the PC as a Business Tool

The personal computer has found new bodies of demand a number of times. I focus here on the circuitous route to the first large markets for the PC as an individual productivity tool for white collar workers.[23]

I revisit the familiar history of the very early PC industry with analytical goals in mind. taking repeated advantage of the gap between what we now know about the uses of the personal computer and what industry participants knew during the 8-bit era, roughly the late 1970s. That lets us understand the role of the information structure of invention at the time. The critical event still in the future was the invention and widespread distribution of personal productivity applications for white collar workers. Market events during the 8-bit era were based on contemporary knowledge of demand – and on contemporary uncertainty about the future of demand.

That information structure of invention helps explain a number of market outcomes in the 8-bit era. Those include the importance of entrepreneurship, market selection of the more open platforms, firms' motivations for supplying open systems, and recombination. Accordingly, I will start with investigation of contemporary information, and then turn to examination of the supply of the two most successful platforms of the era.

There is real analytical value in understanding what suppliers did not know in the early days of the industry. That lets us understand firm strategies which were enabling rather than a planned initiative. It was commonplace in the 8-bit era to think of the main market of the PC as being hobbyists. Here is Microsoft founder Paul Allen in 1977: "The personal computer user finds himself at the leading edge of a new computer applications

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[23] The history of these advances is carefully treated in a number of secondary sources, on which I rely heavily in this section. My account draws on Freiberger, Paul and Swaine, Michael. Fire In The Valley The Making Of The Personal Computer. 2nd ed New York: McGraw-Hill; 2000 (hereafter FITV): on Ceruzzi, Paul E. A History Of Modern Computing. Cambridge, Mass: MIT Press; 1998; on Computer: A History of the Information Machine by Martin Campbell-Kelly and William Aspray, on Langlois, R. N., and Robertson, P.L. "Networks and Innovation in a Modular System: Lessons from the Microcomputer and Stereo Component Industries." Research Policy, Vol. 21(1992), pp. 297-313, and on other secondary and contemporary sources.

and technology, He is becoming a source of expertise and innovation. He is not merely a passive, casual user of hardware and software developed by others."[24] Around the same time, the founder of the commercial PC industry, Ed Robers, forecast most business growth in "inventory, accounting, that sort of thing" i.e. IBM mainframe-like applications for small business.

The most important platforms of the 8-bit era, commercially, were the Apple II and CP/M computers (running the CP/M operating system on a wide variety of brands of computers.) Apple had a sponsored platform but a very open approach to developers. The design of the Apple II made it a mass market PC. The computer came in a plastic case, not metal, and looked like an office appliance more than a hobbyist's technology. It required no soldering, had a keyboard and a monitor, and could run programs. As a result the Apple II, was dramatically easier to use than earlier personal computers (though still quite difficult to use by modern standards.) Accordingly, it appealed to a far larger market than the hobbyist kits could. An important differentiator for Apple was that it used color, which appealed to game developers, but it appealed to the home and school user as well. On the other hand, the Apple II had a 40-column screen, fine for games and school but very problematic for word processing and spreadsheets. These design tradeoffs reflected current technical levels, of course, but also the key fact that demand forecasts were for hobbyist, home, and game.

Ken Olsen, founder and chairman of DEC, famously said in 1977 "There is no reason anyone would want to have a computer in their home." This remark is universally quoted to show that Olsen missed the opportunity represented by the PC. That dinosaur! This gives us an opportunity to be clear on who foresaw what. Contrast with Olsen's remark a contemporary explanation from Apple computer about the uses of its new PC, in a press release:

> Applications include using the computer as a teaching aid for students and for entertainment through interactive games... paddles and joysticks can be in-

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[24] "Software Column" by Paul Allen, VP of Microsoft: Personal Computing, January/February 1977, p. 66. At the time, Allen was Microsoft's "big think" person, while Bill Gates was more in charge of implementation.

> terfaced… a built in speaker sounds when the ball is hit or a photon torpedo is fired at a klingon. Manufacturers [Apple] also suggest home business applications such as financial and bookkeeping analysis, charting the Dow Jones average and home budget tracking. … [W]hen the Apple II is equipped with soon to be announced added components, it will be able to monitor home systems such as heating, cooling, burglar alarm, fire and smoke detectors and lighting. When you're away, the computer can randomly light parts of the house on different days to give the appearance that someone is in residence.

Apple's description of the uses of its machine in Quote 7 2 include (1) immediately visible uses (games and educational software), (2) uses that still have not had any widespread commercial importance for the PC (burglar alarms, home heating, lighting and cooling) and (3) uses that would find a mass market a decade or two later (home finances, which would become a mass market after the introduction of Quicken, and mass market use of online financial services, which would come with widespread use of the Internet.)

The other main platform sponsor, selling CP/M, did not have Apple's marketing savvy, and simply admitted that it was up to others to figure out what the PC was for. "Statistics" and "Economics Research" were among the top uses of CP/M machines in a survey, suggesting a market somewhat smaller than 100s of millions of PCs. The point is, it was not merely Apple and DEC who did not know what was a present and what a future application. It was universal.

The founders of the PC industry did not particularly have white collar automation in mind. (Except in the sense that they had everything in mind.) The first important platform sponsors in the PC industry, who built substantial (100s of thousands of units commercial markets) did not particularly have white collar automation in mind. The first inventor of a PC word processor, Michael Shrayer, who wrote Electric Pencil as a tool for printing manuals for his *real* software products, had WCA in mind only in the narrowest sense.

The inventor of the spreadsheet absolutely had the automation of accounting work in mind. So did the effective commercializer of WordStar, who quickly entered and competed away Electric Pencil's business. The invention and commercialization of these very widely used applications turned the PC into a tool for the individual white collar worker in the corporation. They were not anticipated by the founders of the industry. Indeed, once the inevitable consequences of the conversion of the PC into a white collar tool – IBM's entry, the professionalization of hardware and software supply – many of the founders reacted very negatively. Far from planned, this was a market outcome.

The entrepreneurs of WordStar and VisiCalc built large volume (by then PC standards) businesses because the main PC types, the Apple II and CP/M machines were open to it and had rapidly growing installed bases. Existing PC firms – neither the inventors of the Apple or of CP/M, nor MITS nor Microsoft– themselves pioneering and entrepreneurial – did not invent the new markets, nor did they commercialize them. The shortcomings of these firms (and of established firms like IBM and DEC) were not a limitation on what the market system could accomplish, however, as new firms opened up the new markets. Existing personal computer industry firms were a source of trained managers and potential distribution partners and technical collaborators for the new firms. This specialized and loosely linked structure worked well. It did not need planning nor central coordination to gain economies of scale in multiple products.

By this mechanism, a very valuable GPT cluster, the PC industry used (primarily) by white collar workers, was invented. Once again it arose out of a technically-oriented community, hobbyists and hackers, with narrow goals. This time, that community was not academic science or military demand, but a self-organizing group much like modern open-source movement. They used some of the organizing principles of open science, however, including open systems. Some entrepreneurs would have liked to close systems, but the resource constraints of small firms in a small market left them compelled – recognizing that they did not know everything – to let outsiders innovate. Not only was there a shortage of entrepreneurial knowledge, the shortage was rcognized and impacted business practice in a first order way.

With an important overlap between technical possibility and demand needs seen by no one, the early PC industry followed a circuitous route. The original invention for hobbyists, the commercialization for home users, hobbyists for gamers were inverted by the invention of the word processor and the spreadsheet. This invention was inherently decentralized, as early movers did not anticipate what followed, and in led to a profound acceleration once the high value business PC markets were identified.

Major Mass Market E-Commerce, -Content, -Communication Initiatives

The history of efforts to start mass-market electronic commerce, content, and communication is revealing about the knowledge needed for a planned effort to create a new GPT cluster. The first successful mass-market e-commerce, e-content, and e-communication GPT cluster, the widely used Internet, emerged by a circuitous route marked by inversion. A long series of planned efforts to create such a GPT cluster failed. The planned efforts reviewed in this section were closed, commercial initiatives that drew on the entrepreneurial and technical knowledge of some very impressive market participants. The failures, as we see in this section, arose because their entrepreneurial knowledge was limited, even though it was almost right. Examining them permits us to sharpen the concept of entrepreneurial knowledge considerably. It also shows, once again, the importance of openness in permitting multiple innovators to create what no single planner could.

The same history also shows that a circuitous route can invent something that is not obvious. Here I focus on two aspects of the widely used Internet. An innovation that satisfies a long-felt need, unsatisfied by many prior innovation attempts, is likely non-obvious. When the last key invention in the successful innovation is, from a strictly technical perspective, not a hard problem, the inference of non-obviousness is overwhelming. We shall see that the entrepreneurial knowledge needed to design a successful mass market e-3C platform is what rendered it non-obvious. Open-systems innovation, which as we have seen economizes on scarce entrepreneurial knowledge, was the key to success.

E-Commerce, notably in finance

The potential social value of mass-market electronic commerce, as a broad, general idea, was obvious for many years before the widespread use of the Internet enabled developments in this area. This permits a deep examination of what potential innovators knew, and what they didn't know, in that era.

Why was it obvious? Pre-existing electronic commerce successes, though confined to markets with a modest range of participants, were highly valuable and well understood by market participants. Some of these even extended to individual end users, like bank teller terminals or airline reservation terminals. Bank teller terminals were used both within the firm and across firm boundaries. The treasury function of a large corporation could, for example, have access to account information electronically. Similarly, an airline reservations system could be accessed both by employee sales agents and by external (to the airline firm) travel agents. There were also some limited e-commerce applications which were used by the consumer, such as bank automatic teller machines. Extension of this kind of system to a wider number of markets and a wider number of users was clearly valuable if it could be achieved. The value was obvious.

Home banking and finance systems – now very successful over the Internet – were initiated by a large number of distinct firms. These included some very successful retail banking firms, such as Chemical Bank, Bank of America, Shawmut Bank, and so on. They also included Citibank, which had successfully pioneered the ATM network, one of the most successful mass-market e-commerce applications of the prior era. Contemporary observers thought that these failed primarily through having too small a user base at home, and cannily noted that banking/finance applications alone, including checking brokerage account balances, online trading, online banking, and online bill paying, did not appear to offer enough value to end users to get them to adopt.

The potential social value of mass-market access to information and entertainment online was also, as a broad general idea, obvious for many years. This, too, permits a deep investigation of what the many failed potential innovators knew, and didn't know, beforehand.

Why was _this_ obvious? A number of special-purpose online services had prospered selling high-value information. Lexis/Nexis to attorneys, Bloomberg to the financial industry, DIALOG, and so on.[25] By the late 1980s, there were hundreds of online databases. DIALOG was a database platform; searchers and readers would pay between \$35/hour and \$500/hour depending on the database. Bloomberg, founded in 1981, was founded by a former financial market participant (at Salomon brothers) who saw the benefits of delivering already existing information to financial market participants. They would lease a "Bloomberg machine," i.e., a special-purpose terminal, and get rapid 24 hour access to financial and related information. 180,000. If existing information can be sold in small quantities at high prices to specialized audiences ... then lower value information could also be sold at lower prices in larger quantities to more general audiences.

One strategy undertaken to overcome the problem of limited entrepreneurial knowledge was joint ventures between information content firms and technology firms. (cite to Harrigan's useful review of JVs in this area.) Knight-Ridder, CBS, and Times-Mirror all had collaborations with AT&T. Many had collaborations with IBM. Others tried it in a more go-it-alone way None achieved widespread use

Similarly, a wide number of firms offered communications services to consumers and some to firms. Many of these looked like modern E-mail, and indeed shared some technology with the development of E-mail in not-for-profit settings on the Internet. The end result was also low usage, and the network effects of communications systems create much more value in very widely used systems. By the early 1990s, one could see the odd result that scientists and engineers, surely not the most communicative of people, had excellent access to E-mail, unlike almost everyone else.

There were many of these initiatives, spread out over a wide variety of content compa-

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[25] These successful commercial online services had themselves been invented by circuitous paths, e.g. DIALOG started at Lockheed. See Bourne and Hahn.

nies, joint ventures with existing telecommunications companies, and computer firms. I will not attempt a complete list here (Cite) because the economically important point is that, even taken together, these initiatives did not attract sufficient end-user interest to start a positive feedback loop around mass-market e-content.

A related point follows from the fragmentation noted in this section. Contemporary observers noted that, to attract sufficiently many consumers to create a positive feedback loop, e-commerce sites would need e-content and e-communications services. Fragmentation at an early stage is no vice when there is sufficient openness to permit later technological convergence – that is the whole point of inversion, for example. However, in the case of the plethora of attempts at mass-market e-content, the typical organizational structure of the online services was set up as closed, often through giving control rights to the owners of a particular kind of content While those contractual protections may have had a good economic purpose looking only at local knowledge, they were problematic for creating a broad general GPT cluster involving different kinds of content and service – problematic precisely because lack of entrepreneurial knowledge about those different kinds of content and service.

The fragmentation problem sounds like it could be solved by the creation of a general mass market online platform. If that were to be done as a planned initiative, it would call for entrepreneurial knowledge of the possible developments in e-content, e-commerce, and e-communications (or sufficient openness) to attract many complementary applications, and also for sufficient knowledge of the relevant consumer marketing issues to create a widespread mass market. As we now know, those requirements would be fulfilled by the Internet inversion. The last two prior planned initiatives made an effort to follow the consumer marketing and distribution logic within a closed platform, to which I now turn.

The most successful online service for end consumers before the widespread use of the Internet was AOL. AOL was marketed to consumers as a general online service, and it provided e-mail (to other AOL users) and related communications services. AOL also offered content providers and e-commerce merchants the opportunity to put materials inside AOL's "walled garden." AOL would then distribute those materials online to consumers. AOL was reasonably successful, and it drew competitive imitation from Microsoft. Microsoft created a AOL-imitation online service, called MSN which followed the walled-garden model. There would be e-communications tools for users, and authoring tools for e-commerce and e-content providers who wanted to sign a contract with Microsoft to share revenue. An important advantage of Microsoft's plan was the widespread distribution of the MSN "client" software, which, starting with the release of Windows 95, would be distributed with new computers, an obvious plan to build a mass market.

We did not get to see the AOL-MSN competition that would have followed but for the widespread use of the Internet. Both were quickly competed into irrelevance by the Internet. MSN was withdrawn (confusingly, there was a later Internet website with the same name) and AOL became a "gateway" to the Internet. Absent the widely used Internet, would the AOL-MSN competition have led to widespread E3C with as much innovativeness, breadth of uses, and usage? While it is always difficult to answer a historical counterfactual, at least two important considerations make it clear that the likely outcome would have been significantly slower to develop, less innovative, less flexible and changing, and smaller than today's Internet.

It is worth while to consider this counterfactual. Most of the failures discussed in this section began at an early enough date that there may have been technical feasibility issues in launching an online platform. But the last failure, Microsoft's MSN (I), was launched after the Internet inversion was already underway.

Online services also provide infrastructure so that subscribers can communicate with one another. For example they may have e-mail services or online discussion areas or forums. Online services also provide infrastructure for simple electronic commerce applications. They may broker transactions between content or service providers and their subscribers by charging user fees for using particular services and paying the third parties providing those services. This, at least, was the model for an online service before the widespread use of the Internet. Each online service was a closed system, in competition with the other closed systems.

Subscribers typically pay a monthly fee, and may also pay by the minute they are connected or charges based on what services they use and content they look at. The service licenses in information which it makes available to its subscribers. A large service will license in an enormous amount of content from a wide variety of third party information sources. As a result, the service can connect users with a wide variety third-party information providers.

All of these online services now seem to us to be smaller, less rich, and more expensive than the commercial Internet, and rightly so. They were an effort to fill another felt need ultimately fulfilled by the mass market Internet, that for easily accessible information. Each online service was a closed world, however. Having a Dialog subscription would not get you access to AOL information or vice versa.

Thus, in this long era, technologies that might make the PC into a communications, real-time entertainment, or information gathering tool existed but were narrowly distributed. The Internet ones were narrowly distributed to academic and related communities. The commercial ones were narrowly distributed because of their proprietary or top down nature. There were huge network effects benefits that could follow from a data communications network – being able to E-mail pretty much anyone, for example. Yet these remained latent because no network was ubiquitous.

The last pre-Internet initiative also offers us an opportunity to hear the perspective of the advantages of open innovation in this area from the world's historically most successful implementer of a closed approach, Bill Gates:[26]

> "Subject: Internet as a business tool
> I know I am a broken record on this but I think our plans continue to underestimate the importance of an OPEN unified tools approach for the internet.

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[26] This is an email from Gates on April 6, 1995 to a number of senior Microsoft executives inlcuding those responsible for MSN. It was published as a result of the Antitrust case and is located in Government Exhibit 498. I cite it as Gates 1995.

> The demo I saw today when Windows 95 was showing its Internet capability was someone calling up the Fedex page on the Internet and typing in a package number and getting the status. Imagine how much work it would have been for fedex to call us up and get that running on MSN and negotiate with us. Instead they just set it up. A very simple way to reach out to their customers. The continued enhancement of the browser standards is amazing to me. Now its security and 3d and tables - what will it be within the next several years? Intelligent controls, directory - everything we are trying to define as standards."

Note that Gates is arguing that open innovation is better for the architecture of the overall system, including its interface standards as well as for the permissive nature of new application development in an open environment. This is analytically important because many advocates of planned GPT initiatives assert that planning will produce superior architectures (cites.) There are, of course, cases, in which planned initiatives are better in that regard, but open decentralized market innovation can offer an important competitive alternative.

A related point about the difference between walled gardens and open systems is the potential for transformative innovation by providers of complements. The open Internet has given us a wide number of innovations that run on the server; one thinks immediately of Yahoo, Google, Ebay, Amazon, WikiPedia and Craigslist. The first four of these would have been perceived as duplicative or as competitive threats by a walled garden online service provider, and the last two would have faced difficulty, at the time of their founding, paying for space in a walled-garden environment. The distributed innovation essential to the acceleration of an inversion would have been problematic in an MSN or AOL.

Another reason to believe the pre-Internet initiatives would have gone less far and much less fast is that their proponents anticipated a long, slow growth path. Microsoft, for example, thought that the diffusion of broadband connections to the home would be an important growth driver for MSN, and was (wisely, given their entrepreneurial knowledge) investing in online systems in advance of that development. Historically, the rapid development of the widely used Internet gave consumers a powerful incentive to demand broadband. More generally, the rapid development of E3C software on the Internet has fueled much more rapid investments in hardware, including telecommunications (broadband, wireless, and backbone, among others) and computers. PC demand was roughly trebled by the availability of the Internet, and a wide variety of consumer-oriented hardware devices, from music players to smartphones to tablets, have found new and rapidly growing markets. This tremendous positive feedback loop would have started much more slowly in the counterfactual.

Above, I noted many participants who lacked entrepreneurial knowledge at an early stage. It is worth considering how knowledge changed as a result of the Internet Inversion.

To begin, let me very briefly recount the familiar steps leading to an Internet suitable for mass-market use. After beginning as a military technology, the Internet spent much of its youth as a partly NSF-sponsored communications network in universities, military installations, and some technical companies. In this era, a number of important developments occurred, including valuable add-on facilities for email, for discussion and "social" networking (like Usenet – which is "social" in the sense engineering communities can be, not in the sense that Facebook is), and for sharing datasets and the like among scientists. Two important steps moved the Internet closre to mass market use. The first was the creation of the World Wide Web (WWW) in the computer department of CERN, a physics laboratory. The World Wide Web runs on top of the Internet and provides for a system of interlinked hypertext documents. accessed via the Internet. The WWW was clearly envisioned by its inventors as entirely general (like a number of other networks of the era) and had several useful features which permitted generality, including the use of URLs, a broad open capacity for adding materials, and so on.

The final step toward mass market use was the invention of the web browser at another computer department of another physics laboratory, this one at Illinois. The web browser was almost purely a recombination of existing elements. However, to quote Schumpeter again, while there are “numerous possibilities for new combinations” they are only obvious ex post. Before the recombination, ex ante, “most do not see them.” As a technical matter, the browser inventors recombined the idea of a graphical user interface with some inventions and improvements in that interface (the “back” button) with existing hypertext protocols. The web browser and the open WWW were sufficiently suitable that they began to draw many users, creating the so called "Internet mania."

One of the inventors of the browser first searched for jobs in interactive television, the Silicon Valley rage of the moment, and then became a founder of Netscape, the commercializers of the browser. (Entrepreneurial knowledge is about overlaps, not about envisioning the whole thing.) A venture capitalist who backed Netscape, L. John Doerr noted the dramatic change in the state of knowledge after the creation of the noncommerical "Mosaic" browser:

> "I'd seen Mosaic, the UNIX version of it. ... Marc earned $3.65 an hour, or whatever the University of Illinois had paid him ... and 2 million people were using it. You would have to be dumb as a door post not to realize that there's a business opportunity here.”

That is the hallmark of a change in knowledge, *ex post* obviousness.

Mass market electronic commerce, content, and communication is one of the great triumphs of recombination. It represents a dramatic increase in the value-in-use of a wide number of pre-existing technologies, from the telephone network to the PC, from the server and the database management system to the marketing knowledge of a number of existing retailers. The invention of those pre-existing technologies was financed with knowledge of and in anticipation of their own original markets, not primarily in anticipation of mass market E3C returns, and their recombination represents a social boon.

Mass market E3C was triggered by a series of GPT component invention: the browser, the WWW, and the Internet. Each of these was invented or innovated in low-resource environments but environments where (1) entrepreneurial knowledge showed how a particular problem could be solved in a general way and (2) openness was a natural way to compensate for the resource scarcity.

Conclusion

GPTs that are producer goods call for invention both in general components and in applications sectors. This raises the possibility that the founding of GPT clusters may be beset by the anticipatory problem of recombination. Ex ante, there may be no single locus of knowledge of the precise direction of technical progress which will lead to overlaps between technical opportunity and growth needs. This lack of anticipation does not follow from irrationality or similar phenomenon, but instead reflects the distribution of knowledge across many agents in a market economy.

The ex ante problem of scarce entrepreneurial information has led each of the major white collar automation technologies in computing to be invented by a circuitous route of inversion, decentralization, and acceleration. Important recombinations of these technologies into new more complex systems have also been characterized by much better knowledge ex post than ex ante. Since WCA will continue to be one of the central growth poles of the 21st century, this is an important lesson. Little can be done to solve the problem of scarce entrepreneurial knowledge in this area.[27] Much can be done, however, to preserve the openness and decentralization which have been so important.

Many scholars are tempted to conclude that the Internet inversion, the general purpose computer inversion, or the PC Inversion, involved pivotal steps. To take the largest of three very large literatures, a number of observers have argued that the "countercultural" (in the 1960s political sense) communities involved in the development of the PC were pivotal. Such arguments must be treated very carefully. The logic of an inversion does not say that the particular circuitous route taken to found any particular GPT cluster is pivotal. It is close to saying the opposite – there are a wide variety of paths to collective discovery of a valuable GPT. The "countercultural" nature of some PC innovators, the technical nature of many others, the military and scientific nature of key inventions of the general purpose computer

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[27] There have been numerous failed efforts over the last 50 years to improve ex ante knowledge about WCA. Most have used an engineering approach to organizational design or customer relations.

(or Internet) innovators play two roles in the analysis. The first is that they are example of diversity, especially diversity in entrepreneurial knowledge. The importance of diversity means that few are pivotal. Second, they used open approaches, often because of the very limitations of their entrepreneurial knowledge or their capabilities.

A similar problem applies to the common argument that historical accidents in the founding of GPTs and in recombination are determinative of events for decades if not centuries afterward. Large overlaps between technical opportunity and growth needs can be found, if not quickly, if there are a wide variety of distinct inventive directions in a decentralized economy. A rich market economy can afford a wide variety of initiatives. The lesson we should take away from the particular paths used historically are first, that openness was important to market solutions, and second, that the apparent maturation of some industries (such as the IBM mainframe) can itself be an intermediate stage. Abandoning openness because it has already done its work would be a major error.

References

Aghion, P. and Howitt, P., 1998, "On the Macroeconomic Effects of Major Technological Change" *Annales dl'Economie et de Statistique* (49/50):53-75

Acemoglu, D., 2002, Directed Technical Change, The Review of Economic Studies, 69, pp. 781-809.

Arora, A., Fosfuri, A. and Gambardella, A., 2001, Markets for technology: the economics of innovation and corporate strategy, Cambridge, Mass.: MIT Press.

Athey, S. and Stern, S., 2002, "The Impact of Information Technology on Emergency Health Care Outcomes" The RAND Journal of Economics 33 (3):399-432

Atkeson, A. and Kehoe, P. J., 2007, "Modeling the Transition to a New Economy: Lessons from Two Technological Revolutions" American Economic Review 97 (1):64-88

Incomplete cite, complete.

Bresnahan, T. and Greenstein, S., 1996, "Technical Progress and Co-Invention in Computing and in the Uses of Computers" Brookings Papers on Economic Activity Microeconomics 1996 1-83.

Bresnahan, T. F., Brynjolfsson, E. and Hitt, L. M., 2002, "Information Technology, Workplace Organization, and the Demand for Skilled Labor: Firm-Level Evidence" *The Quarterly Journal of Economics* 117 (1):339-76

Bresnahan, T. F. and Trajtenberg, M., 1995, "General purpose technologies: Engines of growth'?" *Journal of Econometrics* 65 (1):83

Brynjolfsson, E. and Hitt, L. M., 2000, "Beyond Computation: Information Technology, Organizational Transformation and Business Performance" *The Journal of Economic Perspectives* 14 (4):23-48

Cohen, W., D. Levinthal. 1990. Absorptive capacity: A new perspective on learning and innovation. Admin. Sci. Quart. 35 128-152.

Dosi, G., 1982, "Technological paradigms and technological trajectories: A suggested interpretation of the determinants and directions of technical change" *Research Policy* 11 (3):147-147-62

Fleming, Lee, "Recombinant Uncertainty in Technological Search" *Management Science*, Vol. 47, No. 1, Design and Development (Jan., 2001), pp. 117-132

Hayek, F. A., 1945, "The Use of Knowledge in Society" *American Economic Review* 35 (4):519-30

Helpman, E. and Trajtenberg, M., 1998, A Time to Sow and a Time to Reap; Growth Based on General Purpose Technologies. MIT Press, Cambridge, Mass

Jovanovic, B. and Rousseau, 2005, General Purpose Technologies, Handbook of Economic Growth, Volume 1B. Edited by Philippe Aghion and Steven N. Durlauf (c) 2005 Elsevier B.V.

The Burden of Knowledge and the Death of the Renaissance Man: Is Innovation Getting Harder? Review of Economic Studies, January 2009

March, J. 1991. Exploration and exploitation in organizational learning. Organ. Sci., 2 71-87.

Mokyr, J., 2002, The gifts of Athena: historical origins of the knowledge economy, Princeton, N.J.: Princeton University Press.

Nelson, R., S. Winter. 1982. *An Evolutionary Theory of Economic Change*. Belknap Press, Cambridge, MA.

Romer, P.M. "Growth Based on Increasing Returns Due to Specialization" The American Economic Review Vol. 77, No. 2, Papers and Proceedings of the Ninety-Ninth Annual Meeting of the American Economic Association (May, 1987), pp. 56-62

Rosenberg, N. 1996. Uncertainty and technological change. R. Landau, R. Taylor, G. Wright, eds. *The Mosaic of Economic Growth*. Stanford University Press, Stanford, CA.

Schumpeter, J. 1939. Business Cycles. McGraw-Hill Book Company, Inc., New York.

Scotchmer, S., 2044 Innovation and Incentives, the MIT Press.

Weitzman, M.L. 1998 "Recombinant Growth." *Quarterly Journal of Economics*, 63 (2) (May
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