Capitalism as an engine of progress *

Richard R. NELSON
Columbia University, New York, NY 10027, USA

Final version received May 1989

Economists from Marx, to Schumpeter have touted capitalism as an engine of technical progress. But what kind of an engine is it? How does it work? What are the strengths and weaknesses? This essay hazards some answers to these questions [1] Section 1 is a broad theoretical assessment that begins with Joseph Schumpeter's seminal analysis of technical advance as an evolutionary process, but augments it, and then diverges from it in important ways. In particular, it develops the point that the relationships among science and technology, and the institutional structures supporting scientific and technical advance are much more complex than Schumpeter and scholars following in his tradition have recognized Section 2 is the heart of the essay. It draws on a wide range of recent scholarship to describe the different parts of the modern capitalist engine, what they do, and how they mesh. Based on the foregoing. Section 3 develops a particular view of the current debate about strengthening mechanisms to facilitate R&D planning and coordination.

1. The strengths and weaknesses of the Schumpeterian model

Virtually all contemporary general accounts of the capitalist engine are based on Joseph Schumpeter in his *Capitalism, Socialism, and Democracy* [65]. For-profit firms, in rivalrous competition, are the featured actors The context within which they operate is set, on the one side, by the laws and ethos of capitalism which enable firms to keep proprietary, at least for a while, the new technology they create, and on the other, by public scientific knowledge. The latter lends problem-solving power to industrial R&D. The former enables firms to profit when their R&D creates something the market values. Indeed, given that its rivals are induced by this context to invest in R&D, a firm may have no choice but to do likewise The result is significant corporate investment in R&D, generating a bountiful flow of new products and processes. It is left to the market to select ex-post on the innovations offered by different firms, and on the firms themselves.

Given the striking impact that Schumpeter has had on subsequent analysis, it is worth noting that Chapter 7, where the basic picture is presented, contains only six pages. While Schumpeter discussed technical advance elsewhere in that book and in other places, his overall treatment is still very sketchy. It also is worth noting that *Capitalism, Socialism, and Democracy* was written nearly fifty years ago. At that time there was little solid scholarship on technical change. Now there is a lot. [2] Thus it now is possible to evaluate Schumpeter's model in the light of the evidence, to fill in the essential fine structure, and amend or modify as needed, so as to capture analytically the essential system as of his time, and now.

The way I have put the matter suggests that, in the light of what is now known, I still regard Schumpeter as a useful analytic starting place. I do. In particular, I believe his insistence that the system he described sets up technical advance as an evolutionary process is exactly the right foun-

* I am indebted to the NSF, the American Enterprise Institute and the MacArthur Foundation for support of various pieces of the research that has led to this essay. And I am grateful to Moses Abramovitz. Wesley Cohen, Christopher Freeman, David Mowery and Nathan Rosenberg for very useful comments and suggestions on an earlier draft

[1] An earlier version of this paper was published as "Institutions Supporting Technical Progress in American Industry" in Dosi et al. [16].

[2] Each of the following contains an important collection of studies or summarizes large aspects of this literature: Dosi et al. [16], Freeman [20] Rosenberg [54,60] Mansfield [37,38,40] Griliches [25], Nelson [47] and Nelson and Winter [50]. Many of the important studies have been published in *Research Policy*. Cohen and Levin [10] summarize the portions of this literature concerned with the connections between technical advance and market structure.

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dation premise However, Schumpeter never really developed that point and modern scholarship suggests a lot of useful development

Also, many of the details of the modern capitalist engine revealed by recent scholarship are not even hinted at in Schumpeter's coarse-grained picture In particular, neither Schumpeter's model, nor more modern ones at that same level of abstraction, adequately comprehend the complex intertwining of modern technology and science or the rich and variegated set of institutions involved in their advance, that existed even when Schumpeter was writing. And of course Schumpeter could not have foreseen the changes in the nature of technologies and in the institutional landscape that have occurred since his time.

Both of these matters need elaboration. In the remainder of section 1, I pursue these tasks.

1.1 Technical advance as a cultural evolutionary process

Schumpeter said it emphatically. "The essential point to grasp is that in dealing with capitalism we are dealing with an evolutionary process." Empirical research on just how technical advance occurs amply supports this proposition. Technical advance inevitably proceeds through the generation of a variety of new departures in competition with each other and with prevailing practice. The winners and losers are determined in an actual contest. Many contemporary modelers ignore this, treating technical advance as if it proceeded with much more accurate ex-ante calculation and before the contest agreement on winners than is the case. Sidney Winter and I [50] have argued that such models not merely oversimplify, but fundamentally misstate, how technical advance proceeds under capitalism, which is through an evolutionary process in the sense above

Evolutionary processes have demonstrated remarkable power to advance the capabilities of a species, or a technology, and to create effective new ones. However, evolutionary processes are inherently wasteful, and technical advance in capitalist economies is no exception. There are wastes of both commission and omission. Looking backwards one can see a litter of redundant inventive efforts that never would have been undertaken had there been overall monitoring. On the other hand, economies of scale and scope that might be achieved through R&D coordination tend to be missed, and certain kinds of R&D that would have high expected social value may not be done, because individual firms do not see it as profitable for them to do it and no one is minding the overall portfolio. Also because technology is to a considerable extent proprietary, one can see enterprises operating inefficiently, even failing, for want of access to the best technology These firms may be induced to respond by basically reinventing what already has been invented.

Of course the process through which technical advance proceeds in capitalist economies differs in various obvious respects from evolutionary processes in biology. On reflection, some of the apparent differences may be more apparent than real. Thus technology occasionally makes "big jumps". This is inconsistent with traditional concepts of evolution in biology, but not with more modern notions of punctuated equilibria. Also it is clear that innovation is far from a strictly random process; rather, efforts to advance technology are carefully pointed in directions innovators believe to be feasible and potentially profitable. However, here again the difference with biological evolution may not be sharp if one recognizes the possibility (as do some contemporary biologists) that selection has operated on genes to make viable mutations more likely than would be the case were mutation strictly random.

I propose that the feature that most sharply distinguishes the evolutionary process through which technology advances from biological evolution is that new findings, understandings, generally useful ways of doing things, do not adhere strictly to their finder or creator but are shared, at least to some extent. In many cases the sharing is intentional, in others despite efforts to keep findings privy. But in any case, that the new technology ultimately goes public means that technology advances through a "cultural" evolutionary process. The capabilities of all are advanced by the creation or discovery of one. This is fundamentally different from biological evolution.

Schumpeter recognized this clearly. While in his model of technical advance, the lure and reward for corporate innovative efforts resides in the temporary monopoly over the new product or process, he stressed that in the general run of things the monopoly is temporary. Sooner or later competitors will catch on. And he recognized the powerful role played by public science and understood that this made technical advance more efficient. But this is a far cry from arguing that technical advance under capitalism is not associated with considerable waste, at least as can be seen with the vision of hindsight.

It is something of a puzzle, therefore, why the capitalist innovation system has performed so well. There certainly is nothing like the twin theorems of welfare economics around to support an argument that capitalism "can't be beat".[3] But of course this key question is: what are the alternatives? Compared with what? Various socialist scholars have observed the wastefulness of capitalism and proposed that a centrally planned and coordinated system, which treated technology as a public good, ought to be able to do better at generating and using new technology. The troubles socialist economies have been having with their innovation systems suggests that this is easier said than done [27]. The generally poor experience capitalist countries have had when they have tried to tightly plan major technical advances – for example, in civil aircraft and nuclear power – reinforces the point [49].

What is it about technical change that makes effective central planning so difficult, or perhaps impossible? Certainly one important factor is uncertainty about where R&D resources should be allocated in a field where technology is fluid.[4] There generally are a wide variety of ways in which existing technology could be improved, and several alternative paths toward achieving any of these. And almost always uncertainty about where the bets ought to be laid is accompanied by disagreement on this matter among experts. Further, studies done by highly qualified people attempting to assess which would be the best route have commonly after the fact been found to be badly off the mark on one or another respect. Under such circumstances, attempts to get ex-ante consensus are likely to be futile, and appropriately so, because in such a context exploration of a variety of possibilities is called for.

While in principle there are better ways to provide for this, the capitalist innovation engine does define one viable way of assuring multiple sources of initiative, with real competition among those who place their bets on different ideas. And it does so in a context where there is widespread access to the basic generic knowledge one needs to consider intelligently the possibilities, strong incentives to heed market signals, and to cut losses when it is clear one is a loser. One should not confuse the portfolio of efforts thus generated with any kind of optimal portfolio, or presume that the processes through which winners and losers are determined are efficient in any meaningful sense. But this engine of progress has over the years generated remarkable results.

Critic of Schumpeter

It is not apparent how clearly Schumpeter understood the sources of strength of the capitalist engine, or its inefficiencies. He certainly did recognize the creativity, energy, and even stubbornness that went into successful innovation, and the uncertainties involved in breaking new ground. But on the other hand, towards the close of Part II of his *Capitalism, Socialism, and Democracy*, Schumpeter predicted an erosion of the importance of actual rivalry in technical advance as science became more powerful and innovation "is reduced to routine". I shall argue later that this was a bad call.

Regarding the inefficiencies of the engine, Schumpeter clearly recognized that the kaleidoscope of temporary monopolies that are a consequence of rivalrous innovation is incompatible with efficiency of resource allocation in a static sense, but argued that this matters little. Recall his famous salvo, "this kind of competition [innovation] is as much more effective than the other [price] as a bombardment is in comparison with forcing a door, and so much more important that it becomes a matter of comparative indifference whether competition in the ordinary sense functions more or less promptly". He also understood that innovation under the system he described was wasteful, but this too did not seem to bother him much.

There is no question that attempts since Schumpeter to formalize his model have sharpened awareness of these matters. The alleged

[3] I refer here of course to the demonstration beloved by many economists, that given a set of assumptions of great stringency the allocation of resources generated by a competitive system is "Pareto optimal." See, for example, Arrow and Hahn [4].

[4] While many scholars have stressed the importance of uncertainty in R&D, Klein [30] has developed the point with special force. See also the studies conducted under his direction at RAND and published in Nelson [47] and the modeling in Marschak et al. [41].

trade-off between static efficiency and dynamic energy has been modelled by several scholars. We now have models of the costs of "patent races", and recent work has called attention to the fact that the myopia built into evolutionary systems can sometimes lead technology down roads that are far from the best.[5]

However, the point I want to begin making here is that, while Schumpeter's model provides a good starting place, it is too coarse-grained to enable serious examination of the strengths and weaknesses of the modern capitalist engine. A closer look at how technical advance actually proceeds provides not only a more complex picture, but one that is different in important respects.

1.2. The complex capitalist engine

The limitations of the simple Schumpeterian formulation come into view when one studies the advent and evolution of modern technologies like airframes and engines, computers, semiconductors, synthetic materials or pharmaceuticals.[6] The stark Schumpeterian model fails to recognize the variegated nature of modern technological knowledge and the complex and often subtle relationships between technology and science that are essential parts of these histories. Schumpeter recognized that as science grows stronger R&D would become more professionalized. Yet, he missed some of the key consequences. A central one I shall argue is not that technological advance has become more routine, which it has not, but that

1 the generic aspects of new technology quickly become common knowledge among the interested professional community. This phenomena has been an important part of all these histories.

Schumpeter never was explicit about just what he thought science and technology were, or about

2 the nature of their connections, or about the institutional division of labor. However, it is highly likely that he adhered to the conventional wisdom on these matters of his day, and ours. Science is a body of understanding, technology of practice. New science is created by university researchers, seeking knowledge with little heed to practice. Industrial scientists use that understanding to work on what will enhance their company's profits, with little heed to advancing general knowledge. But students of technological advance now understand that matters are much more complex and mixed up than this.

In the first place, technology is not adequately characterized as simply a body of practice. It includes that but it involves, as well, a body of generic understanding about how things work, key variables affecting performance, the nature of major opportunities and currently binding constraints, and promising approaches to pushing these back.[7]

Now this analytic distinction sounds, at first hearing, like the division between technology and science according to the conventional wisdom. And, indeed, in certain technological fields, like the design and manufacture of semiconductors, a good portion of the understanding rests on fundamental sciences like physics and chemistry. However, in almost all technologies a sizeable share of generic knowledge stems from operating and design experience with products and machines and their components, and analytic generalizations reflecting on these. This understanding may have only limited grounding in any fundamental science, standing, as it were, largely on its own bottom. This is not quite what philosophers of science tend to mean when they talk of a "science".

But a number of observers have noted that many modern fields of inquiry that call themselves sciences do not fit the classic mold. Thus fields like computer science, chemical engineering, metallurgy and pathology are basically about this kind of understanding, and reflect attempts to make it more "scientific".[8]

Economists often have put forth the theoretical premise that technology is a latent public good, in the sense of being widely applicable, and inexpensive (if not literally costless) to teach and learn

[5] See for example, Arthur [5] on competing technologies when there are economies associated with the number of users of each and David [13] on how the contemporary typewriter keyboard came into being.

[6] For semiconductors see, for example, Braun and MacDonald [7], Dosi [15], Malerba or Levin in Nelson [48]. For computers see, for example, Katz and Phillips in Nelson [48] or Flam [19]. Miller and Sawers [43] and Mowery and Rosenberg in Nelson are good on aircraft. Freeman [20] provides a good summary of technical advance in synthetic materials. See Schwartzman [66] for pharmaceuticals.

[7] Dosi [14] calls these technological paradigms.

[8] There are several recent accounts of how the engineering fields came into being. See Noble [51] and Kranzberg [32].

compared with the cost of invention or discovery in the first place. On the other hand, some empirical students of technical advance, especially Keith Pavitt [54], have argued strongly that this premise is basically wrong, with industrial technology being very largely firm-specific and costly if not impossible to use elsewhere. The issue here is not trivial. It is important both analytically and institutionally. I wish to argue that both positions are half right. It matters with aspect of technology one is talking about.

generic knowledge

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The notion that technology is a latent public good is a reasonable first approximation, if the focus is on generic knowledge. Generic knowledge tends to be germane to a variety of uses and users. Indeed mastery of such knowledge may be essential if one is to advance or modify prevailing practice with any efficiency. Relatedly, such knowledge is the stock in trade of professionals in a field, and there tends to grow up a systematic way of describing and communicating such knowledge. It is to the advantage of business firms that the young scientists and engineers they hire come equipped with such mastery, so there is a natural harmony of interests between companies and schools regarding its codification.

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Moreover, generic knowledge not only has strong latent public good properties. As the applied sciences and engineering disciplines have grown up directly oriented toward such knowledge in particular fields, and dedicated to its advance and codification, generic technological knowledge has become more and more manifestly a public good among professionals. An electrical engineer or a materials scientist working at the forefront of his or her field has a keen professional interest in news of developments. It is well recognized that the academic parts of these disciplines are by their nature open, with strong individual and institutional incentives to tell the news. What is less adequately recognized is that new generic knowledge created in industrial laboratories also is relatively upon to outsiders knowledgeable of the field. As I shall discuss later in some detail, scientists and engineers in rival firms have a variety of ways to ferret out the generic aspects of a competitor's new technology, even if the specific details of products and processes may remain beyond their ken.

X

particular technique

Regarding publicness or privateness, the body of particular extant technique is more of a mixed bag. Some practiced technique is widely applicable and easily learned by someone skilled in the art, if access were open. But students like Pavitt [54] and Nathan Rosenberg [59,60] have argued persuasively that much of prevailing industrial technique is of little use outside the firms employing it, involving fine tuning to their particular products or processes. And may industrial techniques that operate effectively in a given establishment can be transferred to another only with considerable cost, even if the original operator is open and helpful. Efficient operation of complex techniques in many cases is as much a matter of experience with particular products, machinery and organization, and practice fine-tuned to these through a large number of tacit adjustments, as it is of general understanding plus access to "blueprints" and other documentation. In such cases "technology transfer" may be as expensive and time consuming as independent R&D. [9]

While I have written as if there were a sharp distinction between generic knowledge and particular technique, of course the line is blurry. The locus of the line, and how blurred it is, is partly determined by how patents are drawn up in a field and their effectiveness, matters to which we will return shortly. But to a considerable extent what is generic and public depends on the extent to which the scientific and engineering disciplines have built up a body of general understanding that transcends the specific applications. In no technology is "what works and why" perfectly understood. This is why inventive work is inherently uncertain, or perhaps it is better to regard inventive work as always being uncertain because of a human proclivity to strive beyond what is known scientifically. On the other hand, my argument is that, because of the development of these disciplines, technologies today are much better understood scientifically than they used to be.

The blurry line between generic knowledge and specific application flags attention to the fact that the division of labor between industrial labs and universities in neither sharp nor innate. University laboratories have worked in fields of basic science like physics and molecular biology, but they also have played a significant role in research in the

[9] Recently there have been several good studies of the cost of technology transfer. See for example, Teece [68] and Mansfield [40].

applied sciences – fields like metallurgy, electrical engineering, and animal husbandry – which should be understood as disciplines expressly concerned with the generic aspects of certain technologies. And in a number of fields university laboratories have been an important source of pioneer versions of new technology. One cannot recount the history of fields like computers or the new biotechnologies without noting the major seminal roles played by people at universities.

On the other hand, few accounts of industrial R&D recognize clearly enough that some companies themselves engage in generic research in these applied fields and that the general findings often are published in scholarly journals [10] Most of this work is undertaken in focused search for solutions to technical problems arising in particular design and development efforts. But, as Rosenberg [62] and Cohen and Levinthal [11] have argued, companies in fields where the underlying sciences are advancing rapidly often do research on those sciences in order to stay up with them and to have the capability to exploit developments in a timely manner, from wherever they may come; that is, they join in the community advancing the relevant sciences.

This observation flags two aspects of the modern capitalist engine that are absent from many accounts. First, while new generic knowledge has public good properties, one must invest one's own work in a field to know what to make of the news. Second, those who are in on the news together tend to be active members of a research community. And as members of a community, scientists and engineers are expected to share knowledge. Research communities often are institutionalized as scientific or engineering societies, which hold formal meetings, to which members come to hear the news. And these societies also serve as fora for discussions of research agendas, of where the field is going, who is doing what, etc.

And government agencies are an important part of the modern system. They were moderately important when Schumpeter wrote, and since that time have become much more so. Since the Second World War they have become the principal funders of university research. In some fields, government agencies are major actors in the development of new products and processes. Where a government agency holds a strong interest in a technology, it may try to coordinate private efforts as well as fund them.

Once one sees the differentiated nature of technology and its overlap with science, the wide range of institutions that can be and have been involved in the scientific and technological enterprise, and the major supporting and shaping role played by government, it becomes clear that the simple Schumpeterian sketch misses large parts of the modern capitalist engine, and misspecifies others. When the modern engine is looked at in more detail, one can see features that make it more efficient, more capable of being steered, than the simple Schumpeterian model recognizes. I am not arguing here that the capitalist engine is efficient in the standard sense of that term, or that the wastes and proclivities toward myopia highlighted by simple models are really not there. Rather my point is that the engine is of a much more sophisticated and effective design than simply drawn accounts of it.

2. Institutions supporting technical advance in modern capitalism

In this section I hazard an analytic description of the modern capitalist engine as of the late twentieth century. The level of abstraction will be considerably lower than in the preceding section, and I draw extensively on a number of recent studies of how parts of the system work. I focus almost exclusively on the United States. While I would and will argue that the systems of the other major capitalist nations are of basically similar design, there are some interesting differences. Some of these will be treated in section 3.

I begin my sketch with the proprietary and rivalrous part of the system, the part stressed in most accounts. I shall be concerned with two questions. Why the dominant role of R&D laboratories attached to firms who basically make their money by selling products? And how do they get proprietary advantage from the R&D they do?

[10] See, for example, the studies of publications by scientists working for pharmaceutical companies by Narin and Rozek [46] and Koenig [31].

I then examine an aspect of the system conventionally ignored or underplayed – mechanisms through which firms learn from each other, and cooperate on some matters. These processes and arrangements distinguish a cultural evolutionary process from a biological evolutionary one. My next topic is the role of universities, which I argue is much more complex and variegated than standard views of what universities do. In particular I stress the role of the applied sciences and engineering disciplines as public repositories of generic technological knowledge, and of university research in these fields.

Finally, I turn to different kinds of government R&D support programs, which are an extremely important part of the modern capitalist engine.

2.1. The proprietary domain

2.1.1. The key role of the industrial R&D laboratory

Schumpeter highlighted industrial R&D as the heart of the capitalist engine: organized inventive efforts undertaken by university-trained scientists and engineers, working in special facilities, tied to particular business firms, and focused on advancing their product and process technologies. Many scholars – Christopher Freeman [20], Nathan Rosenberg [60], David Mowery [44], Lawrence Reich [58], David Nobel [51] and David Landis [33] to name a few – have told of the rise of this institutional structure, first in the chemical and electrical industries, and then more widely.

This arrangement now is so familiar that analysts seldom reflect on it. Some of its aspects are relatively easy to understand, and hold in socialist systems as well as capitalist. The key role played by university training clearly reflects the general power the sciences of chemistry and physics had achieved by the late nineteenth century, and the successful development of the new applied sciences and engineering disciplines based on them which were directly oriented to generate knowledge and technique useful in advancing technology. Training in these was largely a job of the universities. The use of people whose training set them apart from on-line workers, the need for special equipment and, sometimes, teamwork, lies behind the widespread use of facilities and management specially dedicated to the R&D enterprise. The desire to shield R&D from pressures to troubleshoot and to permit a longer run orientation called for a certain distancing from on-line work.[11]

It is the tying of the labs to perticular companies that make their money selling products or services (other than R&D) that differentiates capitalist systems from most socialist ones, and this aspect is well worth reflecting on. Why doesn't inventing mostly proceed in organizations that specialize in R & D, like independent or university-affiliated laboratories who do work on contract or sell their inventions to production firms? The fact that these mechanisms are operative to a certain degree affirms that the question is not specious.

The reasons reveal a lot about the capitalist engine. One is that the two factors stressed above – the power of university training in doing industrial R&D and the ability to advance technology in separated dedicated facilities – have limits. To do effective industrial R&D generally requires knowledge about the technology of an industry that is not taught in school. It also often requires a certain amount of close and not pre-programmable interaction between lab and client firm or firms, and complementary work and investment on their part. Thus to be effective, industrial R&D must have close industry links.

In many cases the R&D a firm wants done is closely tailored to its own product and process technologies, its strategy for getting ahead or staying up, and its most pressing needs as it sees them. Thus effective lab work requires not only industry-specific but firm-specific knowledge, and sensitivity of the lab to the needs of its client firm. As stressed earlier it seldom is possible to specify in advance exactly how an R&D project will turn out, and often it is necessary to rethink and respecify objectives along the way. Williamson [75,76], Teece [69] and others argue cogently that such relationships are difficult to govern by contract. Indeed in cases where process engineering is important, or tailoring products to customer demands, technical work may need to be closely integrated with production and marketing and not

[11] Actually, the question of how close to on-line problems and capabilities a lab should work is a central one in R&D management. For a discussion of the history of the issue at Dupont, see Hounshell and Smith [29].

sharply separated institutionally, much less contracted out.

And in many cases tomorrow's high-priority R&D projects tend to grow out of today's and of what is learned in operating experience. A laboratory that did today's work and with whom mechanisms for interaction already are in place has a natural start on tomorrow's work. Thus there are advantages to a firm of durable as well as close bonds with a lab serving it.

These factors calling for close lab–production links are relevant in socialist economies as well as capitalist ones. They explain why the free-standing research institute system of socialist countries has proved such an unsatisfactory vehicle for industrial research, and why socialist economies now are moving R&D into the enterprise. In capitalist economies there also are proprietary reasons for trying lab to enterprise.

Much of the firm-specific information that motivates an R&D project as well as the content of the project will be regarded by the firm as proprietary, and thus the sponsor may want to assure that the lab does not consort with its rivals. As we shall see shortly, in many industries the principal way a firm gains profit from R&D is through exploiting a head start. This requires not only that the details of R&D be kept privy until ripe for practice. To reap returns a firm also must be able to identify and marshal in a timely manner the production and marketing capabilities, what Teece [70] calls cospecialized assets, needed to move rapidly and strongly into the latent market before its rivals can get aboard. Integration of R&D into the firm facilitates such needed coordination.

Of course this is not to say that firms never use laboratories not tied to them, or that independent labs never are important sources of invention. A firm may choose to contract out for relatively routine work or exploratory studies to a lab that has expertise in the field, particularly if that work can proceed with little access to information the firm regards as proprietary. Also, a lab closely tied to a firm may become myopic, leaving room for outsiders to do the real innovating. New firms, or old firms coming into a new business, are a common phenomenon when prevailing firms get conservative. And in circumstances when a new technology is coming into being, and thus there is little relevant specialized knowledge within any industry as of yet, independent or university-affiliated laboratories may be the center of relevant expertise. The current situation in the new biotechnologies is a good example. However, these complications broaden and qualify but do not negate the proposition that the industrial research laboratory is the heart of the modern capitalist engine.

2.1.2. Mechanisms for appropriation and their domain

Above I suggested that one of the reasons firms get their R&D largely done in in-house labs is that this facilitates their appropriating the returns. In this section I turn to means of appropriation more generally.

Schumpeter never was explicit about just how a firm that invested in R&D established and protected a proprietary edge. Economists and historians of technology writing since his time have recognized a variety of means, and their work suggests that different ones are operative in different industries. However, until my colleagues and I designed the Yale survey, there was no systematic map of the terrain. Since the details of the questionnaire and the broad results of our probes about appropriability have been reported in several other places (in particular, see Levin et al. [35]) here I will simply summarize those of our findings that are most relevant to the topic of this section. Some of what I recount will be general, but much of the analysis will be of inter-industry differences. The modern capitalist engine is not just more complex than simple pictures of it, but highly variegated. [12]

To oversimplify somewhat, we distinguished three broad classes of means through which firms can appropriate returns to their innovations – through 1 the patent system, through 2 secrecy, and through 3 various advantages associated with exploiting a first-mover advantage – and asked our respondents in different lines of business to score on a scale from one to seven the effectiveness of these means for profiting from product innovation, and from process innovation.

There were significant cross-industry differences regarding the means rated most effective

[12] The study by Wyatt et al. [77], while directed more narrowly at multinational corporations, covered some of the same ground and came up with similar findings.

for appropriating returns to product innovation. However, contrary to popular beliefs that stress intellectual property rights, in most industries the gains to an innovator apparently come largely from getting there first and exploiting that advantage, rather than by using the shield of a patent, or actively keeping things secret. Included herein are many of the industries generally regarded as among the most technologically progressive, as semiconductors, computers, telecommunication, airframes and aircraft engines.

An interesting characteristic of most of the above industries is that imitation is expensive even if the new product is not protected by a patent. In some, products take the form of complex systems. Our respondents from the industries producing aircraft and complete guided missile systems – canonical complex systems – reported that it would cost a competent imitator more than three-quarters what it cost the innovator to come up with something comparable, even if there were no patent protection at all. Producing complex systems involves many components and many details that need to be got right; much of this learning proceeds on-line rather than in the lab, and is costly and time consuming to do even if one has a model to take apart, or blueprints in hand. These industries and others, like semiconductors, also involve complex production processes with equipment finely tuned to product design. Getting the production equipment in place and learning to run it right is time consuming and costly and by itself can yield an innovator a large and durable advantage over followers.

In these kinds of industries, firms tend to develop differentiated areas of special competence. These particular competencies may be difficult to "transfer" to another firm, even when the former is an active partner in the effort, as when a mother firm tries to enhance the capabilities of a branch abroad, or in a licensing and technology transfer contract. Also, in fields like these, tomorrow's technology often grows out of experience creating and working with today's.[13] Thus an advantage gained by a firm in a particular nook of today's technology is likely to lead to an advantage tomorrow in the same or adjacent nooks. This, rather than durable control over a particular isolated invention, is why the returns to a company of a major initial technical advance may be long term. But to reap those returns requires that it not rest on its laurels.

While I want to emphasize that patents play a much smaller role in enabling innovators to reap returns under modern capitalism than commonly believed, there are certain industries where patent protection is important, perhaps essential, for innovation incentive. Our questionnaire revealed two groups of industries of this sort. One consists of industries where chemical composition is a central aspect of design: pharmaceuticals, industrial organic chemicals, plastic materials, synthetic fibers, glass. The other consists of industries producing products that one might call devices: air and gas compressors, scientific instruments, power-driven hand tools, etc.[14] In both cases the composition of the product is relatively easy to define and limit. These conditions seem to be conducive to ability to draw patents that can be enforced. They also describe a context where, in contrast with the more complex systems technologies discussed earlier, imitation is relatively easy for a competent firm. Thus without patent protection an innovator would gain very little from its investments.

The reports regarding means of appropriating returns from process innovation were different in interesting ways from those about product innovation. First-mover advantages and patent protection were rated less effective in protecting process innovation than product innovation in almost all industries. However, most industries rated secrecy more effective. The lesser effectiveness of patents and the greater of secrecy are probably opposite sides of the same coin. Processes are easier than products to hide from competitors; on the other hand mimicking by a competitor is easier to detect and prove for a new product than a new process.

The lesser effectiveness of first-mover advantages in enabling returns to be reaped from process innovation probably reflects that reduced cost tends to be translated into significantly enhanced market share more slowly than a significant improvement in product design. If market

[13] These technologies are what Winter and I have called cumulative. For good studies of cumulative technologies see Sahal [63], Enos [17] and of course Gilfillan [24].

[14] Our findings regarding where patents are important are similar to those of Scherer et al. [64], Mansfield et al. [40] and Wyatt et al. [77].

share is relatively insensitive in the short run to cost and price, this suggests that incentives for process innovation should be associated with prevailing firm size.

This conjecture squares with the evidence. The bulk of industrial R&D is directed toward new or improved products. Some of the industries marked by high product R&D intensity are highly concentrated – aircraft, for example – others not so, for example scientific instruments. However, in all of the industries where firms spent substantially on product R&D, at least one of the means of appropriation listed in the questionnaire was reported highly effective. In contrast, few industries spend much on process R&D. In those that do, firms tend to be large and the industry highly concentrated.

Of course, the fact that firms in an industry spend little on process R&D by no means implies that no attention is being given to process innovation. In many industries, the bulk of such work is done by upstream firms, material and equipment suppliers. The respondents to the Yale survey reported that upstream firms were an important source of new technology particularly when the industry in question was not concentrated.

This finding is consistent with a proposition put forth by Eric von Hippel [13,14] that the locus of inventive activity is determined, in part at least, by where the ability to appropriate returns is greatest. When an industry is fragmented, if a process innovation is made by a firm in that industry, its level of use is likely to be quite limited, given the relative insensitivity of market share to process innovation. But if process innovations come in the form of new materials and equipment produced by upstream firms, the market is the industry as a whole. It should be noted here that the incentives that locate process innovation upstream reflect real efficiency gains to the economy as a whole. That under capitalism much of process innovation is done by equipment and materials supplier makes process technology more public for firms in the using industry.

Of course it is not one way or another. In many industries firms do some work on their production processes and equipment, and their upstream suppliers also do some work. As argued above, the relative balance seems quite sensitive to the degree of concentration of the upstream industry. It also seems sensitive to the extent to which the needs of equipment users are specialized. Thus von Hippel [74] has shown that the users who do significant invention and design work on equipment tend to have more exacting needs than others in their industry who rely more on suppliers to do the work.

The analysis above is quite consistent with the 'taxonomy" of sectoral patterns of technical advance that has been developed by Keith Pavitt and his colleagues [53]. In particular, in his "supplier-dominated" set of industries, firms are small and apparently not idiosyncratic regarding equipment needs, and rely on upstream suppliers for new equipment. In contrast, in his "scale-intensive" industries firms are large and do considerable R&D on their own. They may also draw from the work of specialized equipment suppliers.

2.2. Technology taking, sharing, and interfirm cooperation

Corporate R&D and innovation yield proprietary capabilities, initially. But generally not completely or for long. Sooner or later other firms ferret it out. Often of course the original innovator will strongly resist competitors getting in the act, but sometimes the innovator is an active party to dissemination. [15]

2.2.1. How proprietary technology becomes public

An industrial R&D laboratory looks two ways: ① toward the firm it serves, and ② towards the external world to monitor developments that yield opportunities or which threaten the mother firm. As Wesley Cohen and Daniel Levinthal [11] have stressed, monitoring is an active process and involves spending resources.

Technical developments of significance to a firm can come from a variety of different places. Technical change in downstream industries can shift the nature of the demands a firm faces. New equipment and materials developed upstream can

[15] The topic being discussed here is akin to that often called the "diffusion" of innovations. However in writings under that rubric there often is a failure to distinguish between the spread of an innovation created upstream among customers, and the imitation of a rival's innovation by competitors. The focus here is the spread of technology among rivals.

profoundly influence what a firm can produce and at what cost. Customers and suppliers generally will help a firm stay up with relevant developments, but if a firm is simply a passive receptor of such information it is unlikely to appreciate its significance, or be able to respond rapidly and effectively. An important part of many firms' R&D efforts involves active monitoring of upstream and downstream technologies.

And of course a firm must stay up with what its competitors are doing. While new generic knowledge is accessible to someone who knows the field well and follows it closely, to stay current in a rapidly moving field generally requires that one have a hand in on the research. And to master the details of new product or process technology created elsewhere may be time consuming and costly, even for a company that has considerable experience with the technology.

In the Yale survey, firms were asked about the effectiveness of various means of acquiring knowledge about new products and processes developed by competitors. These included doing independent R&D or reverse engineering, trying to get information from employees of the innovating firm and perhaps hiring them away, patent disclosures, publications of various sort, and open technical meetings. As in our other probes, we asked separately about product innovations and process innovations. Below I concentrate on the product innovation responses.

Highlighting that monitoring outside technological developments generally is an active and costly business; in most industries the means of monitoring judged most effective was either doing independent R&D (presumably while attending to clues about what one's competitors are doing) or reverse engineering. The industries that gave these means low scores almost invariably were those that do little R&D themselves, hence do not have the capabilities to employ them. Conversely, virtually all R&D intensive industries rated one or both very effective as a means of learning about (and presumably mastering something comparable to) competitors' innovations. It is apparent that in these industries the fact that viable firms have active R&D efforts serves to bind them together technologically, as well as to advance the frontiers.

Those industries that reported reverse engineering to be effective also tended to report that they often learned from conversations with scientists and engineers of the innovating firm. Some reported that hiring away competitors' engineers and scientists was common practice. It is apparent that in the United States in many industries exchange of information among professionals, and interfirm flow of R&D personnel, serve as mechanisms that keep generic knowledge public.

Patents are intended to disclose information, and many of our industry respondents reported they learned a lot from that information. The industries that rated patent disclosures as effective tended to be the same as those who rated patents effective in protecting product innovations – drugs, industrial organic chemicals, synthetic fibers, and also a collection of industries producing devices of various sorts. In many of these industries scrutinizing patents was apparently a prelude to taking out a license, but in some not.

Publications and open technical meetings were deemed effective sources of information in a number of industries. The industries rating these sources highest tended to be of two sorts. Some were connected with health, or with agricultural processing; in these two areas there is a dense web of information dissemination services, largely supported by governments. In others, engineering societies were strong; the metal and metal-processing industries and electronics are good examples.

It is thus apparent that in most industries companies are not able to block information flow to competitors. As noted earlier, Schumpeter understood this well. What may be more surprising, it appears that in many cases they do not try to block information flow, and in others actively support it by encouraging employees to publish, to talk at technical society meetings, etc. Why?

In the first place, the very staking of claims involves the release of information. That is one of the intents of the patent system, and where patents are effective in protecting an innovation they also reveal it. Companies in industries were aggressive use of a head start advantage is important to reaping returns have strong incentive to stake their claim through advertising, open meetings, and a wide variety of other ways, in addition to patenting. They need to attract customers. To do this they need to tell them about their new wares, and this means telling something to their competitors too.

Claim staking and the associated information release is needed not simply to establish legal property rights and lure customers, but also to make stockholders happy, and to attract new capital. It is also often important to let suppliers know of one's new technology, so that they may adjust their own designs and R&D efforts better to serve it.

And to enhance the company's reputation in the scientific and technical world. A reputation for doing first-class work enhances a company's ability to compete for newly minted scientists and engineers, to hire away more experienced ones, and to hold onto its own. More basically, it gets the company, or the key scientists and engineers working there, into the relevant networks. In the pharmaceutical industry, company scientists are major contributors to scientific literature. Scientists and engineers working at IBM, Bell Labs and General Electric have won Nobel prizes for their work. Corporate managers of some firms clearly believe that encouraging their scientists and engineers to be linked-in respected members of the relevant communities is an important investment in corporate prowess to stay ahead of the competition.

It is also important to understand that the divulging of certain kinds of information does not significantly undermine a company's real proprietary edge. Where new products are patentable and patents are effective, as in pharmaceuticals, it does not hurt a company to publish generic information, if it gets the patent. Letting articulated generic information won in R&D go free does not handicap a firm from reaping handsomely from its product innovation, if it has a significant head start on production and marketing of the product in question, and the capacity to take advantage of that lead.

Finally, there are industry-wide efficiency gains to be had by sharing technology. Everyone would be better off if everyone shared. Of course the fact that sharing enhances group welfare does not mean that individual firms have incentive to share. The factors discussed earlier provide some incentive for voluntary sharing of certain information by firms, even if these were not associated with reciprocity. But sharing of information that is important to proprietary interests tends to require something in exchange.

2.2.2. Technology selling, trading, and sharing

Licensing a patent for money is the simplest such mechanism. Surprisingly little is known about patterns and characteristics of licensing, although the last several years have seen several good studies [9,11]. The limited evidence is that much of patent licensing is between a firm and its affiliates or subsidiaries. In a large share of these and other cases, the licensee's plant is located in a different country from the licensor's. And terms often restrict the market of the licensee.

More generally, the evidence seems to be that firms are loath to explicitly license direct competitors, and, other things equal, would rather export or have a plant in a foreign market than license a separate firm in that market. License fees extract only a small portion of the value of the technology to the user. Caves et al. adduce a number of reasons. Two important ones are: first, that in many cases the licensee has the option of inventing around the patent or simply violating it and risking suit; and second, that the decision by the licensor to license generally reflects a judgement that the licensee's market cannot be easily tapped by export or branch plant operation.

This is not to say that there are not situations where firms license their direct market competitors. However, these seem to be in industries where licensees do independent R&D, proprietary gains come largely from a head start in any case, and there is an implicit or explicit reciprocity about licensing certain kinds of technology. [16]

I have little hard data to support this proposition, but I suspect that patent licensing among rivalrous firms, where it occurs, is basically the tip of an iceberg of technology trading and sharing, most of which does not involve explicit licensing. In a number of industries there seems to be a general implicit agreement not to license patents explicitly, but not to enforce them either, even when experience indicates that they can be. The firms apparently recognize that they are better off as a group if they implicitly make a common pool of their technological knowledge, rather than keep

[16] The well-known patent pools in aircraft design and manufacture, automobiles and radio reflect all of these factors. In addition, prior to the pooling firms were engaged in litigation that clearly hurt all or most of the participants.

their individual pools strictly private, and if they all refrain from costly litigation. There is the free rider problem. But I note that these industries, as those where there is explicit patent licensing reciprocity, tend to be ones where a head start is the principal mechanism assuring returns to innovation, and significant R&D is required of any firm for it to keep competitive, even if other firms do not enforce their patents. A company's patent portfolio is largely protection against potential suits of other companies using similar technology, posing the threat of counter-suit. As recent litigation in the semiconductor industry suggests, the agreement not to enforce patents may be dependent upon firms whose technology is being taking thinking they get something in return.

Eric von Hippel [74] has studied several industries in which explicit "technology swapping" is prevalent. When a firm faces a technological problem, an engineer in that firm is likely to call up an engineer he knows in another firm, who often gives help. I noted earlier that in a number of industries conversation with employees of innovating firms was an important source of information about those innovations. Von Hippel argues that when help is given by one engineer to another, an obligation is established wherein the latter implicitly agrees to provide information to the former when the former asks, and the information is at hand to be given. Von Hippel observes that this type of information swapping tends to be most prevalent when the information involved is not of major proprietary importance to the informing firm, in the sense that it would lose a significant advantage over its rivals by divulging that information. But within the limits set by that constraint, voluntary exchange acts to keep down the costs of a proprietary system. [17]

The voluntary divulgence of information in technical society meetings is a matter that warrants careful study, but has received little. My impression is that three things are going on. First, communication between upstream and downstream firms, which willy nilly informs competitors. Data from the Yale survey suggest that where upstream suppliers make significant contributions to technical advance in an industry, technical societies also are rated as important. Second, the sharing of generic findings, partly to enhance individual and company reputation, and partly to keep in relevant networks. Third, the technical society meetings set up the contacts for the kind of exchange von Hippel describes. But to date there has been very little study of these matters.

2.2.3. Inter-firm R&D cooperation

Firms buy, trade and share technological information. To a limited extent they also cooperate in R&D. There are several conceptually separate arenas where R&D cooperation seems quite common.

One is R&D cooperation between a firm and its suppliers or customers. Earlier I noted the role of upstream firms in process innovation in many industries. Often this comes in the form of standardized equipment or materials, but in many cases new equipment needs to be tailored to the particular idiosyncratic needs of the user. In these cases, downstream and upstream firms may each possess different expertise and capabilities relevant to the design of new process equipment that need to be combined for work to go forward effectively. [18]

Cooperative R&D arrangements between a company and an upstream firm, often an equipment supplier, are widespread. There are clearly some proprietary knowledge leakage problems about these arrangements. In particular the downstream partner may not be able to control the manner in which the upstream partner deals with the downstream firm's competitors. The conditions in which these vertical arrangements thrive thus probably involve either strongly idiosyncratic process needs on the part of the downstream firm, or long-term near-exclusive pairing, or acceptance by the downstream firm that the kind of process technology being worked on will not be a competitive item strongly differentiating firms in that industry.

Upstream–downstream interaction is just one example of situations where two or more companies produce goods that are strong comple-

[17] T. Allen [2,3] has described networks among engineers. See also R. Allen [1] on the phenomenon of open access to competitors of new technological developments in steel making.

[18] Freeman [20] provides a nice analysis of the relationships between chemical plant designers and chemical companies. See Lundvall in Dosi et al. [16] for a discussion of long-run vertical cooperation in design.

ments, or have different but strongly complementary expertise or other capabilities, or both. Thus airframe manufacturers cooperate with electronics and engine manufacturers in the design and development of new aircraft. Computer and semiconductor manufacturers often work together. A semiconductor producer that is strong on product design may share information and work together with another company whose process technology is stronger. A new biotech firm with a strong scientific staff but little production and marketing experience, and an established pharmaceutical company with limited in-house R&D expertise in a field where the new firm is strong, may get together on a project or group of projects [19]

The latter are examples of R&D cooperation between firms broadly in the same line of business. These kinds of arrangements tend to be easier to work out when the firms in question are not in strong direct rivalry, producing for example products that appeal to somewhat different customers. As noted earlier, there has long been a tradition of exchange of technological information, and licensing, between firms in the same line of business, but operating in quite different geographical markets.

Yet even where firms are strongly rivalrous they may try to forget agreement to get done cooperatively certain kinds of research where the results are difficult to keep proprietary, or where certain objectives are recognized as shared. There may be industry-wide problems like inadequate procedures for testing raw materials, the solution to which might give little durable advantage to a particular firm, but would significantly benefit the industry as a whole. In many instances an industry can collectively benefit by devising and adopting certain common standards. Setting and advertising these may be useful, for example, in inducing greater efficiency and competition in industries providing inputs, or products that are part of the same system, such as light bulbs and lamps, or television sets and signals provided by television stations. Customers may value highly the ability to use a product of one company together with the product of another, as presently in the case with PCs. As the examples illustrate, there may be serious conflict among companies about whether there should be any standards, as for example when a dominant company like IBM is resistant to other companies making compatible products, or about what the standards should be. But in many cases there is sufficient shared interest to engender a cooperative standard-setting effort. For a good discussion see Besen and Saloner [6].

In recent years there has been a sharp increase in industry interest in mechanisms for cooperative funding of generic research. While this partly reflects a rather mechanical imitation of what is believed to have been fruitful in Japan, it is also the result of a more considered appreciation of some points that I have stressed above. The applied sciences and engineering disciplines have become more powerful. A company that is not linked into their advance is disadvantaged relative to a company that is. And the best way to get linked in is to be in on the research. On the other hand, the public good properties of what is learned in generic research suggest that much is to be gained by sharing expenses.

In 1984 amendments to the Anti Trust laws of the United States were made expressly to facilitate such inter-company agreements. A few such organizations have been formed that stand on their own – for example, the Microelectronics and Computer Technology Corporation, until recently the best known [55], and just recently Sematech. However, by far the greater number of recently created industry-oriented generic research centers have been connected with universities.

2.3. The role of universities

Universities are an important part of the modern capitalist engine. They are a recognized repository of public scientific and technological knowledge. They draw on it in their teaching. They add to it through their research.

Within the United States, university science and engineering, and our science-based industries, grew up together. Chemistry took hold as an academic field at about the same time that chemists began to play an important role in industry. The rise of university research, and teaching, in the field of electricity, occurred as the electrical equipment industry began to grow up in the United States. In both cases the universities provided the

[19] There are a number of recent studies on joint ventures. See, for example, Mowery [45] and Harrigan [28].

industry with its technical people, and many of its ideas about product and process innovation.[20]

Contrary to notions that academic science and scientists stand at some distance from industry, save to provide the latter with people, and published papers, in many fields the links between academic science and industrial science traditionally have been close. Consulting by academic scientists and engineers is not a new phenomenon. And industry scientists have long played a role as advisors to academic science and engineering departments, and as trustees at universities, like MIT, who were training people and doing research of relevance to industry.

Academic science departments can be important to technical change for two quite different reasons: because of the training they provide young scientists and engineers who go into industry, and because of the research they do. To be effective in industrial research, a young scientist needs to know basic principles and research techniques, and these can be taught by academics. The research they do, while almost always good exercise for young scientists, may or may not be directly relevant to industry.

The situation is dynamic, not static. Academic research was very important to technological developments in the early days of the semiconductor industry, but as time went by R&D in industry increasingly separated itself from what the academics were doing. As I will document in a moment, at the current time academic biology and computer science are very important sources of new ideas and techniques for industry. The latter is a new field, and the former is experiencing a renaissance. On the other hand, technologies associated with complex product systems or production processes, like aircraft and aircraft engines, telecommunications and semiconductor production, involve much that the academics do not do, and mostly do not know in any detail.

In our survey, my colleagues and I asked our respondents to score, on a scale from 1 to 7, the relevance of various fields of basic and applied science to technical change in their line of business. We also asked them to score, on the same scale, the relevance of university research. I propose that a high score for a science on the first question signals the importance of university training in that field, and a high score on the second relevance of what academic researchers are doing.

On the first question, every field of science received a score of 6 or higher from at least a few industries. As one might have expected, some scientific fields were of importance to only a few industries. However, four broad fields – chemistry, material science, computer science and metallurgy – received scores of 6 or higher from over 30 industries (out of 130).

The fact that an industry rated a field of science as highly relevant by no means implies that it rated university research in that field so. Thus while 73 industries rated the relevance of chemistry as a field of 5 or greater, only 19 industries rated university research in chemistry that highly. Forty-four industries rated the relevance of physics at 5 or greater, but only four gave that high a score to university research in physics. This does not mean that academic research in physics is unimportant over the long run to technical advance in industry. However, the impact will probably be stretched out and indirect, operating through influences on the applied sciences and the engineering disciplines, with the ultimate impact on industrial R&D occurring through these.

What fields of university research have widespread reported relevance to industry, in the sense that a number of industries credited university research in that field with a relevance score of five or more? Basically, the applied sciences. Computer science and material science head the list, each with more than 25 industries giving such a score, followed by metallurgy and chemistry, with 21 and 19 industries, respectively. University research in the engineering disciplines also received a high relevance score from a number of industries. Industries for which these fields are important look to universities for new knowledge and techniques, as well as training.

Biology, and the applied biological sciences (medical and agricultural science), appear somewhat special today. While these fields are deemed relevant by only a narrow range of industries, those industries that scored these fields at 5 or higher almost always rated university research in these fields at 5 or higher too. Thus at the present time those industries whose technologies rest on

[20] Among the many good studies of the correlation of academic and industrial research in chemistry and electricity are Rosenberg [60], Nobel [51] and Thackray [71].

the basic and applied biological sciences seem to be closely tied to the universities for research as well as training.

It appears that there are two different ways in which academic research feeds into technical advance in industry. In some cases academic research provides the original "inventions" or pilot versions of designs that industry subsequently develops and commercializes. This often happens in the engineering disciplines where research in many cases directly involves building and testing new devices or designs. But in most fields what academic research provides is not pilot inventions but understandings and techniques that industry can later employ for a variety of different purposes. Thus academic research on cancer may provides clues to pharmaceutical companies regarding what to look for, but does not yield an embryonic new design in itself.[21] Of course there are mixed cases. Work in materials science increases knowledge about how to find or create materials for superconductivity. At the same time some academic groups are now in on the hunt for superconductive materials.

In industries where technological advance is being fed significantly by academic research, firms naturally look for close links with university scientists and laboratories where that work is being done. Traditionally, academia has been quite open to those linkages. However, these tend to be located outside the liberal arts and sciences part of the university, in the agricultural experimentation stations, the engineering schools and the medical schools.

In recent years there has been an explosion of new arrangements whereby a single firm or a group of firms funds research at a university laboratory, and receives some sort of advantaged access to that research or its findings. Not surprisingly, the industries most engaged in these activities are ones where firms are large, and who rate academic research as highly important to technological change of interest to them. The major such industries are pharmaceuticals, agricultural chemicals and electronics. And the fields of university science being tapped by those arrangements tend to be those where academic research was judged highly relevant to technological advance in those industries: certain of the biological sciences, and computer science.

Both the federal and state governments have been actively encouraging these arrangements. The National Science Foundation has been supporting Engineering Research Centers which link university research to industry. There is a raft of new state programs that do this. In these arrangements corporate support is often mingled with public support.

My conjecture is that these kinds of new arrangements for greater industry contact with generic research will prove more durable in the United States than the self-standing industry cooperatives. The same free rider problems and technology transfer problems are there, and this limits the magnitude of industry finding. But there are also other parties interested in sustaining these programs – the universities themselves, for one; these arrangements are becoming an important part of academic research and teaching in the affected fields – federal and state governments for another. Fostering technical progress has become increasingly an articulated rationale for public support of university research.

2.4. Government R&D support

Particularly since the Second World War, government R&D support programs have been an important part of the capitalist engine. A variety of government agencies support R&D for different purposes and in different manners, and any attempt at classification hazards oversimplification. However, I find it analytically useful to distinguish among three different kinds of programs.[22]

In one, the guiding purpose is to advance knowledge in certain fields of science. The sponsoring agency may see such advances as salient to its own operational interests, or to its client constituency, but the time horizon is long run and the coupling of projects with pressing practical objec-

[21] The basic distinction is whether industrial R&D workers use the findings and techniques of academic research in going about their problem solving, or whether what comes out of academic research directly invokes particular industrial R&D efforts to exploit those findings. Our conclusions, that the former is common but the latter is not, is quite consistent with Gibbons and Johnston [23].

[22] This section draws draws extensively on Nelson [50].

tives relatively loose. In a second, the government 2 agency in question has a recognized operational responsibility and an associated need for new or better equipment, and R&D is rather closely tied to meeting those needs. In a third, the objective is 3 to meet the relatively short-run needs of an industry or other client population.

These categories should of course be understood as ideal types or models. In fact many government agencies pursue programs that span two or even all of these types. But I would argue that in such cases it is analytically useful to recognize that several different kinds of things are going on.

Thus, let us return to university research. Since the Second World War the United States government has been the dominant source of funding for research at universities. Many people think of the National Science Foundation as the canonical agency for university research support. The mission and program of the National Science Foundation is a relatively clear example of the first kind of program listed above. But significantly before the advent of the NSF, government agencies funded research at universities. The Hatch Act of 1887 provided for Federal funding of agricultural research, much of it at universities. Clearly this program involved a blend of the first and the third described above.

And at the present time, despite the widespread impression that the NSF is the principal governmental source of funds for academic research in the United States, a significantly greater amount of money comes from government agencies with particular applied missions, who are seeking to advance scientific understanding relevant to those missions. Thus the National Institutes of Health are the dominant source of funding of academic research in the biomedical sciences, the Department of Defense the principal supporter of university science in fields like materials science and computer science, the Atomic Energy Commission and its successor the Department of Energy in high-energy physics and nuclear engineering, etc. I noted above the growing importance of programs that fund university research deemed particularly promising to industry.

Of course government funding of basic and generic research is small-scale relative to procurement-tied R&D, where an agency is funding work associated with its attempts to get made and delivered particular kinds of equipment, or to solve particular problems of concern to it. While the DoD is by far the largest spender on procurement-related R&D, many other agencies spend some when they want equipment different from or more advanced than is available on the market. Thus Census, the Post Office, and the Veteran's Administration have on occasion invested in R&D on equipment tailored to their needs.

While there is overlap between the basic or generic research support programs of mission-oriented government agencies, and their procurement-tied R&D programs, I distinguish these on several counts. One is the breadth of the objectives. Another is the way the programs are governed. In research-support programs scientists and engineers from outside government as well as in tend to play a major role in setting broad directions and in making allocation decisions. Universities generally are the locus of work, although government and industry labs may be involved as well. In procurement-oriented programs an office in the government agency makes the decisions and monitors the effort closely. The work is done usually in an industrial or government laboratory.

The massive defense procurement-related R&D programs of the last quarter century are so familiar to contemporary observers that it is seldom recognized that this phenomenon, like broad government support of university research, dates from the Second World War. Prior to then, much less R&D went specifically into the design of military equipment, and a large share of what did was financed by companies themselves as an investment in possible future government sales. There are several reasons why the Pentagon shifted from the earlier policy of letting companies invest in R&D to a policy of government finance of R&D on systems and components that it intended to procure when they were ready. One is simply that during the war the armed services worked with companies in that mode, and the habit became natural. A second is that, largely because their demands be~~cause~~come more ambitious, the armed services wanted greater control over the R&D on the systems they wanted. As it turned out, in the post Second World War era, both aspects of the military R&D programs, the broad research support aspect and the particular development and procurement aspect have pulled into place a number of technologies of enormous civilian significance, including modern semiconductors, the electronic computer and jet aircraft. Various observers have remarked on this, and have gone on to argue that DoD R&D has been the key to United States technological supremacy in commercial products during the 1960s and 1970s. However, this clearly was not a principal intent of the DoD.

Which brings me to the third type of program I listed – R&D support expressly to enhance the capabilities and competitiveness of an industry. This is where much of the current discussion of appropriate government R&D support policies is focused. And despite the cluckings of some who should know better that the United States never has and never should engage in such "industrial policies", it is apparent that the United States certainly has, and will continue to do so.

I noted earlier that support of agricultural research dates back now over a century. While much of that work has been located at universities, it has been specifically aimed to help farmers and, in some instances, farm product processing industries. And much of the work has been aimed at solving particular practical problems.

In a number of instances, the procurement interests of a government agency, particularly the armed forces, have been used to argue for policies to help an industry commercially. Thus RCA was formed at the explicit urging of the U.S. government to assure that the U.S. had a strong indigenous radio industry, a matter deemed important for national security. The NACA was organized through government to help the U.S. airframe industry compete internationally so as to assure a procurement base. The recent formation of Sematech was justified by the argument that a commercially competitive semiconductor industry is essential to national security. The U.S. program in support of civilian nuclear power also grew out of national security concerns, and the desire to exploit spillover.

This is quite a mixed bag. Recent policies that move further in this area include Sematech and the collection of university-based industry-oriented centers mentioned earlier. However, perhaps the most interesting aspect of the current policy discussion has been the proposal that the government take responsibility for coordinating both academic and industry work in emerging fields like superconductivity and high-definition T.V. What to make of this idea?

3. Towards a socialization of R&D?

3.1. The evolving roles of government

The modern capitalist engine is always in the process of being redesigned and rebuilt. I began this essay with Schumpeter's characterization of the American engine, circa 1942. At the time he wrote, several of the important pieces of the contemporary system described in section 2 were not yet in place. The strong publicly supported university research system, and the massive military R&D programs, were components added only after the Second World War. And even the part of the system he highlighted – large companies with large attached laboratories – was relatively new then and nowhere near as prevalent as it became after the war.

Schumpeter well understood that the capitalist engine always was being redesigned. And he had some strong notions regarding where the redesign ultimately would go.

While most scholars of technical advance fasten on those few pages of Chapter 7, in fact the central argument of *Capitalism, Socialism, and Democracy* was that the capitalist system he was describing would sooner or later be transformed into a socialist one. He put forth a number of reasons. One he deemed as particularly important was that it was increasingly becoming possible to achieve major technical advances without the wastes associated with the capitalist way. "... innovation itself is being reduced to a routine. Technological progress is increasingly becoming the business of teams of trained specialists who turn out what is required and make it work in predictable ways. The romance of earlier commercial advantage is rapidly wearing away, because so many more things can be strictly calculated that had of old to be visualized in a flash of genius." [23] Thus the arguments for capitalism were eroding.

How right was this call? Are we indeed seeing a replacement of the capitalist engine with one of basically different design?

[23] For a discussion of Schumpeter's sometimes schizophrenic views see Langlois [34]. For the more radical stance, see Veblen [72].

I have argued throughout this essay that the modern capitalist engine is a much more complex mechanism than Schumpeter's famous sketch suggests. It is, indeed, a much more socialized system. I have stressed the rise of the applied sciences and engineering disciplines, the codification of generic technological knowledge, and the professionalization of R&D and related activities, as important forces for the socialization of technological knowledge, and to some extent of R&D. Here, Schumpeter's call clearly was on the money.

Certainly government's role in the system has expanded since Schumpeter wrote, not only in the U.S. but in the other major capitalist nations. Everywhere governments have taken responsibility for the funding of university research, and for a good portion of higher education in science and engineering. In other countries, as well as the United States, government agencies dependent upon the advance of certain fields of science and technology for the success of these missions have made large investments in the advancement of these fields. Everywhere bodies exist to do at least a modicum of coordination of national efforts in fields judged strategic.

However, if by socialization one means explicitly planned and coordinated action across a broad field of activity, then socialization is still quite limited. There does indeed seem to have been a significant increase in R&D cooperation in some industries, partly as a result of government policies encouraging this and partly as a result of the firms' own volition. But in the United States and elsewhere the vast bulk of civilian-oriented industrial R&D is funded by the companies that expect to benefit from it. Among firms in the same line of business, while there is increased cooperation on some matters, rivalry is still the general rule.

What about Japan? A number of analysts have highlighted features of the Japanese R&D system that differentiate it from the American and European: the role that MITI plays in helping industry chart out appropriate broad directions, the coordination of public and private actions, close interaction between companies and their component and equipment suppliers and occasionally among competitors in pre-competitive research. A strong case can and has been made that these features add power and efficiency to the Japanese system.[24]

I would argue, however, that the Japanese system is not of fundamentally different design from the American, but rather is a different and perhaps more effective model in the same broad class. One distinctive part of the present Japanese system is concerned with cooperative pre-competitive research. As the name implies, the results of this kind of work are difficult to make proprietary, at least immediately and directly. And as generic knowledge has grown stronger, it has become increasingly important to industry that it keep a hand in on its advance. The Japanese accomplish this in their particular way. But as I argued above, U.S. companies are being drawn down into similar kind of work too, if through different mechanisms, generally in association with universities. There are differences and changes going on in this arena, but they don't seem to involve a radical system redesign.

Many observers have pointed to the mechanisms orchestrated through MITI by which technologists in Japan get together and share knowledge and judgements about where technology is going and attempt to map out coordinated action. But I have above mentioned that mechanisms for sharing and coordination are not unique to Japan, and recent policies in the U.S. and in Europe are concerned with strengthing these. Again, the differences and changes would appear to be of degree, not of kind.

And in Japan, as elsewhere, the vast bulk of industrial R&D continues to be work done privately, and companies compete fiercely. Attempts by MITI to guide and coordinate R&D have been resisted when companies felt they encroached on proprietary turf.

And Schumpeter's prognostication that as science grew stronger technical innovation would become predictable and routine has turned out to be a bad call. Since Schumpeter's time a number of large-scale and far-reaching R&D programs have been predicated on that belief, almost always with bad results. While the problems of cost overruns and far off-target performance that have marked American military procurement have been interpreted by many as symptoms of weak management, greedy contractors, and undue and perhaps somewhat corrupt cronyism, it is evident that

[24] For an especially perceptive analysis see Freeman [21]

in most cases both the DoD and the contractor vastly underestimated the uncertainty and the difficulty of the far-reaching task they agreed to take on. And since there was no real competition or alternatives, pressures to cut losses were weak. The problem the U.S. had with its nuclear reactor programs, the ill-fated SST, and now with the space shuttle, tell a similar story. The European record with large-scale ambitious and sheltered projects is no better. While MITI has tried to guide and coordinate industrial efforts, the focus has tended to be on pre-competitive R&D, and there certainly has not been tight planning of new product development. In the United States, while the discussion has been particularly sharp, it would appear that the proposals that a government agency coordinate work on superconductivity and high-definition TV are aimed at pre-competitive research. Indeed it is highly unlikely that the companies involved would tolerate efforts to coordinate their product design work.

But then, for product and process innovation, the old messy process of letting a number of different parties make their own bets using their own money and relying on ex-post evaluation to decide what course was the right one still has a lot to argue for it over a policy of ex-ante technology-wide planning and administered coordination. It, appropriately, stimulates a variety of approaches in circumstances where it is a mistake to narrow down exploration to a very few. And it serves as a guard against technological hubris of an organization that would be czar.

So I return to my starting place. Schumpeter's quick characterization remains a good first cut at understanding the capitalist engine and its workings. It is a much more complex machine than he described and over the years it has grown even more so. Over the years we have learned to do many things to make the original engine run more efficiently, with more power and less waste, and have learned to steer it at least broadly. We share knowledge, and coordinate action in certain situations. Public funding and government leadership have been used to make generic knowledge more readily public, and to guide and spur the system when this has seemed appropriate.

The structures Japan has developed over the last fifteen years are further steps in these directions. However, rather than changing the basic nature of the engine, the new elements are better seen as cutting down some of its roughness, reducing some of its inefficiencies, enhancing its effectiveness, without significantly diminishing the role played by pluralism, rivalry and ex-post selection. Technical advance under capitalism still needs to be understood as proceeding through an evolutionary process.

And so too the changes in the nature of the capitalist engine itself. At the present time a wide variety of new kinds of organizations, new ways of doing things, new patterns of inter-organization interaction, are coming into being in the United States and elsewhere. As with the advance of technology, many different actors are involved in these changes in the system, with very little in the way of overall planning and coordination. And like technical advance, institutional change is very much a cultural evolutionary process. Firms watch other firms and try to learn from their experience. When technical advance appears to be going better in one country than another, a variety of new departures are induced in the latter with the aim of emulating elements of the former's system. For years the U.S. was the world's model; now obviously Japan is.

But as with technological innovation, these new departures regarding the way of going about doing technological advance must be understood as changes that may or may not succeed. Probably, some will, and will become entrenched, and some will not, and will disappear after a while. This openness of the engine to experimental tinkering is one of its greatest design virtues.

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