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SCIENCE AND TECHNOLOGY POLICY FOR THE ASIAN NICS:

LESSONS FROM ECONOMIC HISTORY

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I

The subject of this conference is "Science and Technology Policy" and the specific topic that I have been asked to address is the "Lessons from Economic History."

It is not necessary to belabor the point that science and technology are immensely powerful forces that have been fundamental to the process of economic development in the advanced industrial economies of the world. The reason that this conference is being held, and sponsored by AID, is because we already believe that. The more interesting questions, surely, revolve around how science and technology have exercised their influence, what factors have determined their effectiveness and, not least, what have been the connections between science and technology. These are questions that I propose to address primarily in the context of American industrial history.

Let me begin by putting certain intellectual cards on the table. Science and technology are each areas of human activity where the gains from specialization have been immense. Analyzing the nature and the extent of these gains are activities that, in turn, have been at the heart of much economic analysis since at least the time of Adam Smith. Indeed, economists' eyes are apt to glaze over at the very use of such language as "the gains from specialization." True to the notion of division of labor, we look around for the appropriate specialists to whom we can pass the buck of responsibility for dealing with subject such as science and technology. As an economist I have no difficulty in honoring an intellectual division of labor that absolves me of having any competence in these matters - although I cannot quite repress the wish that some professional colleagues would stop flaunting their ignorance of these subjects. It is at least barely possible that economists might be better

economists if they understood a little of what goes on in the realms of science and technology.

Which brings me to my central point. Although research in the realms of science and technology are obviously highly specialized activities best left to the appropriately-trained professionals, I believe science and technology policy are entirely different matters. Insofar as our present interest in these subjects is due to their economic consequences, I would like to assert that the formulation of science and technology policy is inseparable from the formulation of economic policy.

Some clarification and elaboration are in order. Putting the point negatively, it is not possible to isolate science and technology policies from economic policy making without seriously diminishing their effectiveness. In fact, it is difficult even to identify a very specific set of science-and technology-oriented programs and label them as "Science and Technology Policy." The reason is that there are a great number of factors that affect the commitment of resources to science and technology, and that determine the "output" that society is likely to derive from such use of resources. Science and technology are economic activities, and they represent ways of pursuing a wide range of economic goals and objectives. They are not activities that run along some parallel track to, let us say, the Departments of Energy, Transportation, Defense, or Agriculture. Nor can they readily be isolated in a Department of Science or a Department of Technology.

It is, in fact, likely to be highly damaging to the effectiveness of science and technology if one limits one's thinking specifically to matters that touch upon these areas only in direct and immediate ways. The reason is that the economic payoffs will depend upon the strength of existing incentives and

capabilities for exploiting technology. This includes, of course, existing technology and not just newly-available technologies. In the context of developing countries, of course, even the distinction between existing and newly-available technologies necessarily becomes blurred. A technology may have been employed in Western Europe or North America for several decades without being "available" on the Indian subcontinent. An effective technology policy in India may well have the consequences of speeding up the transfer to, and the exploitation in India, of technologies long utilized in more highly industrialized countries. Precisely because less developed countries are usually far from the technological frontier, there exists the possibility of adopting and utilizing technologies that are not the outcome of research or development activities in less developed countries themselves. But success in bringing about the international transfer of technology is likely to be, as I will argue, the outcome of economic policies generally, and not policies specifically directed to science or technology.

This last paragraph suggests a point that needs to be made explicit. It is important not to exaggerate the dependence of technology upon science. In a favorable economic environment, much technological change will take place without science. This is, of course, especially true in less developed countries, for whom a wide range of technological alternatives are available, at least in some sense, from overseas sources. Conversely, in economies where the economic environment is hostile, even a very large volume of resources devoted to R&D will have a low payoff.

II

A lesson that I think we have been learning from economic history is that economists have been making use of overly-simple conceptualizations of the innovation process. In this "standard" conceptualization, innovation has been seen as a linear process, which begins with scientific research at a basic level. Occasional breakthroughs at this level lead to fundamental changes in the way we understand the physical world. This enlarged understanding, in turn, suggests applications in particular realms and therefore gives rise to research of a more applied nature. These more detailed findings eventually become embodied in the design of new products or processes, activities in which engineers and technologists play roles of increasing significance. The particularities of the activities of technical personnel depend heavily upon the specific industry, and will be very different in pharmaceuticals, where testing upon animal and then human subjects plays a critical role, as compared to aircrafts, where prototypes must be designed, tested and, eventually, flown. New products that emerge are passed along to specialists in marketing, and a new product is born.[1]

The essential feature of this conceptualization is that innovations originate "upstream" at the level of scientific research, and flow "downstream" in a reasonably orderly fashion from scientists to engineers and product designers and, ultimately, into the market place.

When stated in this way, the conceptualization is an obvious caricature. Reality is far more interesting. In particular, innovative activity is not, and never has been, as intimately locked into prior scientific research as this model

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[1] See Stephen J. Kline and Nathan Rosenberg, "An Overview of Innovation," in R. Landau and N. Rosenberg (eds.), The Positive Sum Strategy, National Academy Press, 1986.

implies. It is hard to resist the observation that this model has been as popular as it has been among academics in part because it attributes a critical priority to scientific research of the kind performed at universities, and because it therefore allows the reasonable inference to be drawn that the way to encourage more innovative activity is to provide additional financial support to university research.

Furthermore, this intellectual framework has received strong support from neoclassical economics, which has treated the central economic problem of innovation as emerging out of a form of market failure due to the nonappropriability of the findings of basic research. According to this view, market economies will make socially inefficient investments in research because of the inability of the investing firm to capture and to privately appropriate the findings of that research. In Arrow's classic formulation:

> Thus basic research, the output of which is only used as an informational input into other inventive activities, is especially unlikely to be rewarded. In fact, it is likely to be of commercial value to the firm undertaking it only if other firms are prevented from using the information. But such restriction reduces the efficiency of inventive activity in general, and will therefore reduce its quantity also.[1]

It is not my purpose to deny the existence of market failure, nor to deny the fundamental importance of the insights of Arrow and Nelson on the limitations of market forces in providing adequate incentives to inventive activity. However, economic history, I suggest, indicates that this is a highly incomplete analysis of the problem. In particular, the neoclassical model pays

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[1] Kenneth Arrow, Economic Welfare and the Allocation of Resources for Invention," in The Rate and Direction of Inventive Activity, Princeton University Press, 1962, p. 618. See also the earlier formulation by Richard Nelson, "The Simple Economics of Basic Scientific Research," Journal of Political Economy, June 1959.

insufficient attention to sources of invention that originate downstream, sometimes far downstream, without any dependence upon prior science; it ignores a range of critical considerations affecting the utilization of new knowledge; and, a main concern for present purposes, it strongly suggests that policy ought to focus upon subsidizing "upstream" research. Thus, the policy implications that flow from this view are most important, because they point unremittingly to the urgency of overcoming market failure by strengthening the incentives to produce new knowledge, and pay little or no attention to strengthening the capability for applying, or further diffusing, existing stocks of knowledge.

The focus on appropriability distorts the analysis of the process of innovation in other ways. The neoclassical analysis focuses largely on the incentives of firms to invest in R&D and views internal structure and process as unimportant.[1] As a result, it devotes little attention to the process through which the findings of research are actually converted into commercial innovation. According to this view, new technologies represent the application of "previously-acquired" scientific knowledge--usually meaning "recently-acquired" scientific knowledge. Thus, technological innovation is regarded as essentially the application of "upstream" scientific knowledge to the "downstream" activities of new product design and the development of new manufacturing processes.

In reality, however, many of the primary sources of innovation are located "downstream," without any initial dependence upon or stimulus from frontier scientific research. These sources involve the perception of new possibilities

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[1] The remainder of Part II draws heavily upon a forthcoming book, Technology and the Process of Economic Growth, by David Mowery and Nathan Rosenberg, to be published in 1989 by Cambridge University Press.

or options for efficiency improvements that originate with working participants of all sorts at, or adjacent to, the factory level. The participants include professional staff such as engineers and those who have responsibilities for new product design or product improvement, and may include customers as well, as von Hippel has noted.[1]

The acquisition of knowledge for innovation is not a once-and-for-all matter. Rather than a unidirectional, one-time occurrence of transfer of basic scientific knowledge to application, the processes of innovation and knowledge transfer are complex and interactive ones, in which a sustained two-way flow of information is critical. The ability to adopt a new technology, to evaluate a new technique, or even to pose a feasible research problem to an external research group, may require substantial technical expertise within the firm.[2] It is here that we locate one of the basic deficiencies of the neoclassical emphasis on appropriability. The fact is that it requires a great deal of technical competence on the part of a firm before it can effectively utilize knowledge that is one some scientific or engineering shelf in the world outside

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[1] See Eric von Hippel, "The Dominant Role of Users in the Scientific Instrument Innovation Process," Research Policy, 1976. See also Nathan Rosenberg, "Learning by Using," in Nathan Rosenberg, Inside the Black Box, Cambridge University Press, 1982, chapter 6.

[2] Concerning Japanese technology imports from the industrialized West, Caves and Uekusa stated, "The level and pattern of research and development within Japan are closely related to the import of technology from abroad. Firms must maintain some research capacity in order to know what technology is available for purchase or copy and they must generally modify and adopt foreign technology in putting it to use. A 1963 survey of Japanese manufacturers showed that on average one-third of the respondents' expenditures on R&D went for this purpose. The moderate level, wide diffusion, and applied character of Japan's research effort are consistent with a facility for securing new knowledge from abroad." Richard Caves with the collaboration of Masu Uekusa, "Industrial Organization," chapter 7 in Hugh Patrick and Henry Rosovsky, Asia's New Giant, The Brookings Institution, 1976, p. 126.

the firm. By focusing so heavily on the conditions necessary for the generation of new useful knowledge, and ignoring the conditions that need to be fulfilled to assure effective utilization of that knowledge, the neoclassical approach has, in effect, constructed a bridge that terminates abruptly halfway across the stream.

Moreover, the process of technical innovation has to be conceived of as an ongoing search activity that is shaped and structured not only by economic forces that reflect cost considerations and resource endowments, but also by the present state of technological knowledge, and by consumer demand for different categories of products and services. Successful technological innovation is a process of simultaneous coupling at the technological and economic levels--of drawing on the present state of technological knowledge and projecting it in a direction that brings about a coupling with some substantial category of consumer needs and desires.

In fact, effective decision making within the firm involves drawing upon several different kinds of expertise. The choice among technological alternatives and the decision as to how much performance improvement is worth acquiring involve commercial and economic judgments as well as technological criteria. There are typically many ways of strengthening a bridge, or reducing the weight of a commercial aircraft, or improving the conductivity of an electrical transmission system. The exchange of information among specialists in establishing the optimal trade-off is therefore a central part of the firm's decision-making process.

A recent book by Nelson and Winter contains an insightful examination of these characteristics. A central component of their view of innovation is the portrayal of the discovery of alternatives, as in research, and the choice among

alternatives, as in the decision to pursue development of a discovery, as a single process, rather than separate activities.[1] R&D is portrayed as a particular type of search activity, consisting of repeated "draws" dorm a distribution of possibilities that may be more or less "distant" from a firm's existing endowment of skills and technological capabilities. This view of innovation, and of knowledge more generally, has two central elements. A great deal of the knowledge that is important to the operation and improvement of a given process or product technology is "tacit," i.e., not easily embodied in a blueprint, operating manual, or the mind of a single technician or engineer. A closely related characteristic of technical knowledge is the fact that much of it is highly firm-specific and results from the interaction of R&D and other functions within the firm.

The process of R&D has often been equated with innovation. If innovation consisted solely of R&D, understanding innovation would be far simpler and the real problems would be far less interesting. Successful innovation requires the coupling of the technical and the economic, rather than being solely a matter of "technology push" or "market pull", in ways that can be accommodated by the organization while also meeting market needs, and this implies close cooperation

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[1] "Orthodox theory treats 'knowing how to do and knowing how to choose' as very different things; we treat them as very similar. Orthodoxy assumes that somehow 'knowledge of how to do' forms a clear set of possibilities, bounded by sharp constraints, and that 'knowledge of how to choose' somehow is sufficient so that choosing is done optimally; our position is that the range of things a firm can do at any time is always somewhat uncertain prior to the effort to exercise that capability, and that capabilities to make good choices in a particular situation may also be of uncertain effectiveness." Richard Nelson and Sidney Winter, An Evolutionary Theory of Economic Change, Harvard University Press, 1982, p. 52

among many activities in the marketing, R&D, and production functions.[1] The research that goes on within this internal cooperation and communication process is not usually considered as science, but it is essential to successful innovation. The importance of these types of research has been underestimated in the recent past, probably in part because of the use of an oversimplified linear model of innovation that entirely omits them as categories of research.

III

I turn now to an examination of the role played by science in the halcyon days of America's thrust to industrialization: The 40 or 50 year period ending with the outbreak of the First World War. These were the years in which American made the decisive transition from a primarily agricultural economy to the most powerful of all industrial economies. How can the role and the economic contribution of science be characterized?

The central point that needs to be emphasized is that the application of scientific knowledge to industrial purposes has to be understood primarily in terms of the changing needs of the industrializing world, and not primarily in terms of newly-emerging scientific knowledge. It was, of course, true that the expanding scientific knowledge of the realms of the new world of electricity and the much older one of chemistry played roles of increasing significance in

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[1] See David Mowery and Nathan Rosenberg, "The Influence of Market Demand upon Innovation: A Critical Review of Some Recent Empirical Studies," Research Policy, April 1979.

shaping the content of innovative activity in the late 19th and early 20th centuries. But I will argue that, even in these realms the application of scientific knowledge has to be understood in terms of the changing specificity of needs in the industrial world; and equally important, the scientific knowledge that was being applied was rarely new or recently-acquired knowledge. It was, much more commonly, knowledge that had been available for many years, and it was knowledge that would surely have been classified as old and elementary, and not recently captured at the research frontier.

In the post-Civil War years improvements in transportation in the U.S. destroyed the earlier isolation of small local markets that were catered to by small-scale, locally-oriented industry, and played a major role in creating a large, internal market of continental scale.[1] This market was also growing rapidly in terms of population, per capita income and extent of urbanization. For a number of reasons, cultural and social as well as economic, it was a market that was apparently prepared to absorb products of a higher degree of standardization and uniformity than was the case in Europe. At least there seemed to be fewer obvious obstacles. In any case, firms in these industries grew to a larger absolute size, and on the whole attained large size earlier than elsewhere (In the construction industry, the growth of firm size was particularly conspicuous among the suppliers of construction materials). Bigness in this respect was critical; it created a vast range of problems, but also opportunities, that required control of inputs and their qualities to a

[1] The following discussion of the economic role of science draws upon Nathan Rosenberg, "The Commercialization of Science in American Industry".

degree that had not previously been nearly so significant.[1] In addition, larger scale required careful attention to numerous aspects of the new production processes, in which more precise regulation and control were essential to successful performance. This was notoriously the case with the new, large-scale production technologies in metallurgy. Moreover, there were significant changes in the nature of the final product, often involving quite exceptional, or precisely-defined, performance characteristics that were essential to economic success. Thus, the baker producing on a larger scale could not make purchases from the miller, the Pennsylvania Railroad could not buy steel products from the rolling mill, nor could the urban construction firm make purchases from the cement manufacturer, without the assurance of certain precise performance or quality specifications for these purchased inputs. Failure to meet precise specifications was likely to be commercially disastrous, but it was increasingly likely to pose a threat to life and limb as well.

The point is that the pattern of industrial development that began to emerge in the late 19th century has to be understood not only - and perhaps not even primarily - as the emergence of new bodies of scientific knowledge that were subsequently applied to industry. Rather, the central feature is a rapidly growing and industrializing economy that encountered all sorts of situations at the level of newly-emerging technologies where further improvement and progress required drawing upon the existing fund of scientific knowledge. It is often pointed out, when discussing the earliest industrial research laboratories (say before 1900, or even much later) that they were not yet performing activities

[1] Note that this discussion does not require growth in size of firm to the extent of involving a significant degree of market concentration, although this kind of growth did indeed frequently occur.

that should be regarded as research. Rather, they were engaged in a variety of routine and elementary tasks such as the grading and testing of materials, assaying, quality control, writing of specifications, etc. It is certainly correct that these were the primary uses to which science was first put in an extensive way in the industrial context. Science, when it entered the industrial establishment, came to perform tasks that were elementary <u>from the point of view of their science content</u>. In a research program devoted to the history of science, such activities would properly merit little attention, if any. Very little of the work of scientists in industry before the First world War was of interest to anyone concerned <u>exclusively</u> with science and its progress. But that is not, or ought not to be, the relevant criterion here. From the point of view of industrial growth, the work of these scientists was absolutely vital. It is difficult to envision how the emerging industrial technology could have functioned successfully without the kinds of information that could only be readily supplied by scientifically-trained personnel. Competitive success increasingly went to those industrialists who were the quickest to perceive and to exploit these opportunities. Carnegie could not help gloating over the advantages conferred upon him by his decision to employ a trained chemist:

> We found ... a learned German, Dr. Fricke, and great secrets did the doctor open up to us. (Ore) from mines that had a high reputation was now found to contain ten, fifteen, and even twenty per cent less iron than it has been credited with. Mines that hitherto had a poor reputation we found to be now yielding superior ore. The good was bad and the bad was good, and everything was topsy-turvy. Nine-tenths of all the uncertainties of pig iron making were dispelled under the burning sun of chemical knowledge.
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> What fools we had been! But then there was this consolation: we were not as great fools as our competitors ... Year after we had taken chemistry to

> guide us (they) said they could not afford to employ a chemist. Had they known the truth then, they would have known they could not afford to be without one.[1]

The substantive point at issue here goes far beyond that of Carnegie's percipience, or the ability of one firm to derive a competitive advantage in a particular market or industry. The point is much more far-reaching. The industrial growth of the United States coincided with a geographic expansion over a vast continent. It is widely agreed that one of the most distinctive aspects of American industrialization was the extraordinary richness of the natural resource environment within which it took place. Such mundane scientific techniques as chemical analysis, evaluation and assaying played a crucial role in identifying and providing guidance to the speedy and efficient exploitation of hitherto unexplored and untapped mineral resource deposits.

The industrial history of America in the decades before World War I has, as a central feature, the application of elementary scientific knowledge or methodologies in ways that had large economic payoffs. In steel, a critical aspect of the process by which steel came to be widely used was the development of new products that optimally achieved the specific combination of performance requirements of a growing number of specialist users of steel. The widening diffusion of steel and its applications to new uses strengthened the economic importance of understanding its characteristics and performance properties. Such concerns about precise performance characteristics persist even today. (Examples: automobiles, aeroplanes, modern oil refineries, steel as construction material in skyscrapers.) In both construction and manufacture of increasingly complex products, the metal inputs need to be produced to a high

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[1] Quoted in H. Livesay, Andrew Carnegie, Boston, Mass., Little, Brown and Company, p. 114.

degree of uniformity and predictability. Failure, under certain circumstances, could be disastrous, as was the case with respect to large gun forging, steam turbines aboard ocean going vehicles, or the structural members of large-open bridges.

Similarly, concrete was not extensively used as a building material until late in the nineteenth century. Like steel, its large scale use came after the introduction of a new European technology -- in this case the rotary kiln, which had been invented in England in 1873. Like the earliest British experience with the Bessemer process, its introduction was beset by difficulties that were ultimately traceable to the failure to exercise sufficient chemical control over the composition of the raw material inputs. As in the case of steel, its eventual performance was extremely sensitive to variations in the processing as well as to variations in the composition of the inputs, since the transformation of a wet plastic into a rigid material involves some complex chemical reactions.

These achievements were made possible by the systematic application of chemical analysis to the raw materials employed in the manufacture of concrete -- lime, silica, alumina, iron, oxide, and associated impurities. The first major step was the identification of the aluminum and silicon oxides as the active ingredients in the production of hydraulic limes, even though the underlying chemistry of the process by which concrete eventually "sets" was not to be grasped for several decades.[1]

Concrete was far from the only instance of scientists being drawn into work for the construction industry as a result of the growing use of a material. Scientific knowledge (primarily chemical) also was applied to the industrial

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[1] See Carl Condit, American Building, University of Chicago Press, 1968, chapters 13 and 14.

uses of wood. This took place at several levels. The Department of Agriculture had long included a Division of Forestry that had emphasized the use of scientific principles (or what were thought to be scientific principles) in growing timber as a crop ("silviculture"). However, the problems confronted by industrial users of wood went far beyond the application of such principles. This was recognized by the establishment of a federally financed Forest Products Laboratory at the University of Wisconsin in Madison, Wisconsin. This laboratory, which opened in 1910, conducted research on all question pertaining to the use of woods for industrial and construction purposes.[1]

The economic benefits flowing from the systematic chemical testing, grading, and classifying of the woods of the immense and heterogeneous forest lands of the United States were considerable. A more exact determination of the composition of woods, and the linking of composition to performance characteristics, made it possible to utilize resources far more efficiently. One immediate result of chemical testing was to establish that some tree species were far more useful than previously believed. Although white oak was strongly preferred for the making of railroad cross ties before 1890, subsequent research revealed that chestnut oak and post oak were "perfectly interchangeable" with white oak.[2] Similarly, "... studies of southern pines demonstrated that bleeding trees for turpentine in no way damaged the strength of the timber. Trees that had been bled for many years were therefore no longer

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[1] For a detailed institutional history, see C. A. Nelson, A History of the Forest Products Laboratory (Ph.D. dissertation, University of Wisconsin, 1964). It is worth mentioning that, in the year 1910, the lumber industry was, by a wide margin, the largest single industrial employer in the United States, employing 700,000 workers.

[2] Ibid., p. 50.

excluded from the bridge timber markets."[1]

More significantly, the research that led to important improvements in techniques of wood preservation by chemical treatment eventually made it possible to make routine use of wood that was abundant in many regions and that was unsuitable for use on cross ties in an untreated condition. Far and away the most important chemical treatment was impregnation with creosote, a coal-tar derivative. Treatment with creosote rendered "inferior" woods usable and substantially prolonged the useful life of the better woods. The proportion of cross ties treated with chemical preservatives rose to over 20 percent in 1910, over 75 percent in 1930, and over 95 percent by 1950. the number of wood-preserving plants in the United States increased from 14 in 1900 to more than 70 in 1907, to 102 in 1914.[2]

Finally, chemical and physical testing identified the precise performance requirements of each end use so that a finer matching of specific end use with specific wood input became possible. With such information, the high quality woods were used only where they were needed, and cheaper, lower quality woods were introduced wherever higher quality wood could be dispensed with. Thus, a detailed knowledge of physical properties made possible a more efficient matching of specific grades of wood to the wide range of possible end uses.

In the closely related pulp and paper industry, research conducted at the Forest Products Laboratory laid the technical basis for the southern pulp and paper industries that emerged during the 1930s by making possible new uses for previously "inferior" woods.

Previously Southern pines has been used to make 'kraft'

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[1] Ibid., p. 50.

[2] Ibid, pp. 104, 111.

> paper, a strong, brown paper, useful for wrapping exclusively. During the 1920s the FPL experts discovered a modified sulfate process which, in combination with a new two-stage bleaching process, permitted the manufacture of strong, white paper from Southern pines good for book and magazine paper. The so-called 'semichemical' process, which ranks among the most outstanding of the many FPL accomplishments, was also developed at FPL during the 1920s. This process featured a combination of the chemical and mechanical pulling methods of reducing wood substance to fiber form. The process revolutionized the pulp and paper industry by providing a method for the successful pulping of hitherto useless hardwoods."[1]

There is an important common denominator running through the industrial histories of metallurgy and construction before the First World War: Commercial as well as technological success increasingly depended upon the ability to predict accurately the performance of both inputs and outputs. The growth of mass production metal-using industries and the remarkable new feats of construction all relied upon the ability to push materials to new limits and to predict the performance of these materials with a high degree of confidence. This involved bringing together in a systematized way the knowledge of the behavior of materials that had been gleaned from the work of scientists and engineers working on these materials in innumerable industrial contexts. These activities were crystallized in the formation, in 1902, of the American Society for Testing Materials.

These developments were the outgrowth of the attempt to set objective standards. For, assuming one could demonstrate the relevance of given standards in quantitative terms, such standards were still of limited usefulness unless tests and instruments could be developed that predicted reasonably well the actual performance in service, and unless these tests and instruments yielded

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[1] Nelson, op. cit., p. 223.

at least roughly uniform results in different places and in different hands. This codification of knowledge concerning the performance of materials formed the basis for writing specifications that covered a large part of the economy. It provided a scientific basis, in terms of uniformity and reliability of materials, for the design and manufacture of complex capital goods and the high-performance consumer durable goods that came to play an increasingly important role in the course of the twentieth century.

The benefits of quality control, standardization, and precise predictability in the performance of materials are so pervasive, and so central to industrial efficiency, as to defy brief summarization. Consider food processing. The producers of processed and preserved foodstuffs required both precise predictability and uniformity of the composition of their inputs, because "The form of spoilage to which a food is susceptible depends on its composition, structure, specific micro-organisms and storage conditions. Micro-organisms themselves are affected by temperature, moisture, oxygen concentration, available nutrients, degree of contamination with spoilage organisms, and the presence or absence of growth inhibitors."[1] Similarly, for large bakeries operating with formulae that required precise gluten measurement, any deviation is unacceptable. Furthermore, the internal requirements of the milling processes that were being introduced during this period demanded more precise measurement and control to attain the essential goal of uniform grinding characteristics.

Such innovations required chemical analysis and control, and the new milling technologies brought with them the establishment of laboratories for

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[1] Encyclopedia Britannica, 15th edition, "Food Preservation."

testing the wheat and the flour to establish their precise chemical composition - protein content, gluten content, moisture, ash, and so on.[1] Chemistry soon discovered that criteria formerly in use were misleading. "The great difficulty is that the system of wheat-grading now in use emphasizes certain external factors, such as hardness, plumpness of kernel, color, and weight, which do not always correlate closely with milling quality. This the cereal chemist have shown is largely dependent on the chemical composition of the wheat; its protein content and the quantity and quality of the gluten it contains."[2]

Similar prosaic applications of elementary scientific knowledge resulted in the development of new products from a number of unlikely sources. Systematic analysis of the chemical composition of waste products in the meat packing industry led to the extraction of useful products in sectors such as pharmaceuticals, soap, commercial fertilizers, explosives, lubrication oils, etc. A similar search for uses of petroleum by-products led to the extraction of a range of products that it is hard to conceive of as ever having constituted waste - gasoline, naphtha, paraffin, petroleum jelly, lubricants and a large host of products based on tar derivatives. Although, as I have emphasized, the exploitation of byproducts involved the application of scientific techniques, they involved some other basic economic considerations as well. One of these

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[1] "The need for quality control along scientific rather than merely empirical lines was felt at least as early as 1886, when A.W. Howard founded a commercial testing laboratory at Minneapolis to which millers sent their flours for baking tests and for analyses of their contents. Stimulated by Jago's work on the chemistry of flour, the Washbur Crosby Co. set up a testing room in 1893 - the first such step to be taken by an American miller. Today every large miller determines precise quality standards for his products, of whatever kind, and bends every effort to see that they are maintained." John Storck and Walter Teague, Flour for Man's Bread, University of Minnesota Press, 1952, p. 315.

[2] Charles Kuhlmann, The Development of the Flour-Milling Industry in the United States, Houghton Mifflin Company, Boston, 1929, p. 231.

is, of course, relative prices. Whether it pays to utilize a previously discarded byproduct depends on its price and the price of the products for which it may be a close substitute. Indeed, what is a product and what is a by-product (or potential by-product) depends upon the cost of bringing it to market, upon the prices of other products for which it is a potential substitute, and upon the level of technological and scientific knowledge. Although the hide of a cow and the tallow were regarded as valuable by-products of the meat packing industry in Chicago, on the Argentine pampas earlier in the nineteenth century cattle were slaughtered merely for their hide or tallow--as Marx indignantly observed in Capital.[1] More recently, natural gas, a high-quality fuel, was flared for many years because of the absence of satisfactory techniques of pipe manufacture. In the early history of petroleum, everything aside from kerosene (which was highly desired as an illuminant) was considered to be a by-product. Petroleum was not regarded as an energy source. Subsequent technological change--in the form of internal combustion and diesel engines--changed all that.

The ability and the financial incentive to exploit waste materials depended, in addition to the availability of scientific knowledge, upon a central trend in the process of industrial development: the growth in scale of production operations. Marx saw this clearly in the last years of his life (he

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[1] "While simple cooperation leaves the mode of working by the individual for the most part unchanged, manufacture thoroughly revolutionizes it, and seizes layout-power by its very roots. It converts the laborer into a crippled monstrosity, by forcing his detail dexterity at the expense of a world of productive capabilities and instincts; just as in the States of La Plata they butcher a whole beast for the sake of his hide or his tallow." Karl Marx, Capital, Modern Library Edition (New York: The Modern Library, 1936), p. 396.

died in 1883).[1] Indeed, in the history of individual industries we find case after case in which the increasing scale of production operations eventually gave rise to an awareness that certain materials of great potential usefulness were being discarded in large quantities. Since techniques for utilizing these materials did not yet exist, this awareness often led to the necessary research activities, sometimes to the original establishment of a research laboratory. Thus, growth in scale commonly raised the private financial returns to investment in scientific research, leading to the acquisition of new techniques for the utilization of by-products.

Such developments were particularly common in the growth of chemical processing industries such as petroleum refining. The origin of the central research laboratory for the Royal Dutch Shell Oil Company's American subsidiary has been characterized as "... an attempt to make profitable uses of the tremendous amounts of oil field and refinery gases which had up to then been flared into the air or, at best, burned for boiler fuel." The important of developing a research thrust to utilize these by-products was closely linked to the growth in scale of plant: "The quantities of these gases were at first

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[1] Production on a large scale, Marx pointed out, offers certain decisive advantages. Among them: "We refer to the reconversion of the excretions of production, the so-called waste, into new elements of production, either of the same, or of some other line of industry; to the processes by which this co-called excretion is thrown back into the cycle of production and, consequently, consumption, whether productive or individual. This line of savings ... is ... the result of large-scale social labor. It is the attendant abundance of this waste which renders it available again for commerce and thereby turns it into new elements of production. It is only as waste of combined production, therefore of large-scale production, that it becomes important to the production process and remains a bearer of exchange value ... In the chemical industry, for instance, excretions of production are such by-products as are wasted in production on a smaller scale; iron filings accumulating in the manufacture of machinery and returning into the production of iron as raw materials, etc." Karl Marx, Capital (Moscow: Foreign Languages Publishing House, 1959, 3:79, p. 100.

insignificant, but with rapid expansion of cracking facilities in the second half of the Twenties, the volume of cracking gases became enormous."[1]

Nevertheless, although the search for by-products led to systematic laboratory research in the twentieth century, the earlier search for petroleum by-products in the nineteenth century was the work of practical people or those with only a modest amount of chemical training. Before the turn of the twentieth century the value of these "by-products" (gasoline, naphtha, paraffin, petroleum jelly, and lubricants) was equal to the value of the main product--illuminating oil.

IV

A central thrust of this discussion is that the organization of research activity needs to be undertaken with a primary focus upon the emerging and changing needs of the industrial community, and not upon the kinds of knowledge that are being produced at the frontiers of science. The critical issue is how to create the institutions and the incentives to exploit the existing body of scientific knowledge and techniques.

Here an obvious historical lesson is the absence of any single mold or model that was appropriate across a wide range of industries or disciplines. Indeed, the diversity of institutional mechanisms that emerged in the American

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[1] K. Beaton, Enterprise in Oil: a History of Shell in the United States (New York: Appleton-Century-Crofts, 1957), pp. 502-3, as quoted in David Mowery, The Emergence and Growth of Industrial Research in American Manufacturing, 1899-1945 (Ph.D. disc., Stanford University, 1981, p. 123.

context is most striking, and it is fair to say that the underlying rationale for the particular pattern that emerged and succeeded is not very well understood and requires more attention. For not only, in the American case, did it include a huge growth of in-house industrial research, on the one hand, and an expansion of university-based research, on the other. In addition, by the outbreak of the First World War there were also a number of specialized institutions exercising responsibilities that seemed to be uniquely adapted to the peculiar needs of some sector of the economy. In agriculture there were the land-grant colleges and the agricultural research stations whose educational, research and knowledge-diffusion activities were fine-tuned to the needs of farmers at the state level. But there were also specialized organizations such as the National Bureau of Standards, The National Advisory Committee on Aeronautics, the Forest Products Laboratory, and the American Society for Testing Materials - the last an interesting example of inter-firm cooperation sponsored by a professional engineering society. These organizations obviously provided their members with very different services as well as very different incentives. Their economic effectiveness for exploiting a growing body of scientific knowledge is still not very well understood. What is interesting and provocative, by comparison, say, with the organization of research in the Soviet Union, or other centrally-managed economies, is the absence of a single model imposed upon different sectors of the economy.

Four significant features appear to have been connected with the American experience:

(1) There was a roughly simultaneous growth in research activities within private industry, the academic community and the public sector. This suggests that there may have been some common underlying force, or set of forces,

accounting for a rising social payoff to research activity. Moreover, that rough simultaneity raises important questions about the relationship of these separate research activities. To what extent, and in precisely what ways, did these activities depend upon, and draw upon, one another? How strong were the complementarities between public and private sector research, or between academic and business-supported research?

(2) Within the business community itself, research in the United States had a particular feature that distinguished it, at least in degree, from western European patterns. That is, a much larger fraction of business-supported research was conducted within the firm, and not by some form of industry-wide association or other arrangement. Independent research organizations that were not affiliated with manufacturing firms declined in importance during the first decades of the 20th century. To a much greater degree than appears to have been the case, say, in Great Britain[1], the growth of research in the United States was directly linked to considerations of business strategy at the level of the individual firm.

(3) There appear to be well-defined limits to the extent to which a firm can overcome certain deficiencies by relying upon services available through the market. A careful analysis of the activities of independent research organizations and those of the in-house research laboratories of manufacturing firms for the period 1900-1940 seems to support this conclusion.[2] It appears

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[1] See David Mowery, "British and American Industrial Research: A Comparison, 1900-1950," paper presented at the Anglo-American Conference on the Decline of the British Economy, boston University, October 1, 1983.

[2] David Mowery, "The Relationship between Contractual and Intrafirm Forms of Industrial Research in American Manufacturing, 1900-1940," Explorations in Economic History, October 1983.

that, for this period, a firm undertaking complex or risky innovation projects had little choice but to do so in-house. In fact, the ability of the firm the exploit even the limited services that were available via contract was affected critically by the presence of an in-house laboratory. Firms that lacked such in-house expertise typically utilized contract research primarily for relatively simple purposes, such as chemical analysis. Alternatively put, the independent and in-house research laboratories were complements during this period and performed different research tasks. A firm could not readily overcome low levels of internal technological or scientific sophistication by purchasing it in the market place.

(4) The most successful institutions have in different ways tackled the complex and subtle problems of creating close interactions among the various specialized people who play a role in innovation. Achieving the right combination of information flows, on the one hand, and incentives on the other, seem to have been vital ingredients of success. Institutional arrangements that worked well were characterized by close and candid exchanges of information between those performing the research, on the one hand, and those responsible for the management of production, and of marketing, on the other. In particular, the achievement of commercial success, as opposed to purely technological success, usually required feedback loops that provided valuable information, drawn from experience that flowed "upstream" to those involved in

product design and modification.[1]

Historical experience suggests that the great economic and social benefits of science are likely to flow from science at a very applied or, to use an earlier adjective, prosaic level. It is a mistake to think about science in the manner that is most congenial to academic scientists: as pushing out the frontiers of knowledge. The great utility of science from the point of view of its contribution to economic development, comes from its ability to solve problems that are very elementary, indeed even uninteresting, from the point of view of the research scientist working at the research frontier, or from the point of view of the historian of science who is likely to be preoccupied with issues of historical priority or influence.

Less developed countries are in any case not likely to be major contributors to pushing out the frontiers of science. The critical questions for them are how to create the institutions and the incentives that will effectively link applied science with improved technologies and improvements in the performance of their economies. The thrust of my argument is that effective science and technology policies are not separable from economic policies that have the effect of raising the payoff to investments in the improvement of scientific and technological capabilities. It also implies that there are specific complementarities between public and private institutions that must be better understood in order to provide a basis for reshaping institutions as well as policies.

An instance where it seems that these concerns have not been accorded sufficient importance and attention is the Indian case. India represents what

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[1] Stephen Kline and Nathan Rosenberg, "An Overview of Innovation," op. cit.

appears to be a case of low payoffs from a relatively well developed and extensive scientific and technological infrastructure. I believe that this has a lot to do with the way R&D is organized in India and, in particular, with the extremely tenuous links between the various public and private institutions that are involved in the process. It also has a lot to do with economic policies and institutions which fail to provide adequate incentives for the effective utilization of the "output" of R&D.

For example, in India, over 80% of R&D is paid and performed by the government.[1] The overwhelming proportion of this is performed in over 200 research institutes, almost all controlled by ministries or departments located in New Delhi. The structure is un-wieldy and heavily bureaucratic. It does very little in the way of integrating applied research activities with the more "upstream" activity of basic research; neither does it meet its avowed objective of coordinating the research projects undertaken in the various government owned research laboratories.

These features are indicative of the kind of thinking that seems to have formed the basis of the science and technology framework in India. For one, the process of producing useful knowledge - the innovation process - seems to have been visualized as a linear process, with the implication that the major problem was seen as commitment of sufficient resources for "basic" and "applied" research in a way which would minimize unnecessary duplication of research. The second major implication of this point of view was that the <u>utilization</u> of the product of research activities was not seen as a real issue; rather it seems to

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[1] By contrast, in the US, the government funds around 50% of the research and does 14% of it. The South Korean government funds only 27% of the R&D and the corresponding figure for Japan is 24%.

have been more or less taken for granted. The functioning of a major research Indian institution - The Council for Scientific and Industrial Research (CSIR) - exemplifies these points.

The CSIR used to account for an extremely large share of industrial R&D in India - 78% in 1968. In the past decade its share in the total industrial R&D expenditure of India has come down to around 20-25% as manufacturing firms in both the public and private sectors have increasingly undertaken in-house R&D. Despite the vast amount of resources allocated to the CSIR, it has failed to make any discernable impact upon the productivity and efficiency of the industrial sector in India. One major reason for its failure seems to have been the fact that its research activities were at times effectively insulated from information about the needs of the public and private sector firms which would be the ultimate users of their output. For example, studies showed that most projects tended to be initiated by scientists themselves and that users of technologies generated by CSIR labs tended to be confined to firms situated in close geographical proximity.[1] A related problem was that work on these technologies was terminated at the prototype stage. This left the later development process to the potential users who were completely disassociated from the earlier research activities, and therefore commonly lacked any basis for intelligent decisions with respect to the possibilities for manufacture and subsequent commercializations of the technology.

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[1] For more details, see Behrman, J.N., Industry Ties With Science and Technology Policies in Developing Countries, Oelgeschler, Gunn & Hain, Cambridge, 1980.

Crane, D., "Technological Innovation in Developing Countries," Research Policy 6, 1977.

Dagli, V., Science and Technology in India, S. Chand and Co., New Delhi, 1982.

The Indian case illustrates a major theme of this paper: Successful research requires specific institutions to facilitate and enhance communication between the different stages of the research and production process and to make possible a quick and low-cost flow of information. The specific institutional forms would vary across sectors and would depend on the nature of the complementarities between universities and public and private manufacturing institutions. Equally important, successful research requires that the scientific and technological.

The Indian experience underlines the point that success in one policy direction usually depends upon achieving success in other directions as well. The development process appears to be full of complementarities, which makes it unlikely that a less developed country can achieve accelerated growth at low cost through some technological fix or, in this case, even through the building up of a substantial scientific and technological infrastructure. Economies that generate low rates of capital formation and are unable to acquire additional assistance from abroad, or that impose heavy bureaucratic and regulatory constraints upon private decision making, are unlikely to find passage to a rapid growth trajectory in science and technology policies. History suggests that countries that have managed to grow rapidly have done so by doing <u>many</u> things right, not just one or two things. With respect to such policies, it appears that potential payoffs may be very high, but only if science and technology are perceived as complements to effective economic policies, not as substitutes.

V

We turn, finally, to a brief consideration of the Japanese historical experience. There are a number of reasons why that experience is of particular relevance to the Asian NICs. Japan began to industrialize under conditions that were vastly different from those of America, and those conditions more nearly approximated those of other Asian countries. Whereas America began to industrialize under circumstances of a vast abundance of resources, Japan in the late 19th century was densely-populated and resource-poor. Agricultural as well as industrial resources were very limited. Furthermore, Japanese factor proportions in general more nearly resembled those of her Asian neighbors, in that it was an economy in which capital as well as natural resources were scarce relative to labor. Finally, Japanese government policy, from the beginning of the Meiji period, was consciously and forcefully devoted to bringing about a rapid transfer of western technology.

As Ranis pointed out many years ago, the Japanese were extremely skillful in learning to adapt western technology in a variety of ways to suit domestic needs. In textiles they showed great ingenuity in adapting western machinery so as to reduce the capital/output ratio. In textiles, for examples, they purchased older, second-hand machines - often machines that had already been discarded in Lancashire as obsolete. Moreover, once installed, they operated the machinery at higher speeds and for longer hours than was the prevailing practice in England or America, and they lavished greater amounts of labor on servicing the machines and maintaining them in a decent state of repair.[1] These and other kinds of "capital-stretching" adaptations have also been successfully

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[1] Gus Ranis, "Factor Proportions in Japanese Economic Development," AER September 1957.

introduced in other rapidly-industrializing economies of Asia such as Taiwan and South Korea.[1] A valuable lesson to be drawn from these capital-stretching adaptations is that it is often a serious mistake to associate a fixed factor-intensity with a given piece of industrial hardware. When a country has developed a sufficient technological capability, there are often widespread opportunities for substituting labor for capital when making use of western industrial machinery.

It is noteworthy that Japan at first did not immediately understand the need to adapt foreign technology to domestic circumstances. Dutch water control technology, for instance, was introduced without considering that, in addition to tidal forces, mountain run off was a major source of flooding.[2] Similarly, the Japanese government in 1871 imported a vast mechanized silk reeling plant from France. While it was intended as a model factory, private business discovered that it could not profitably operate such capital-intensive plants.

However, the Japanese government learned from its initial mistakes and, subsequently using modified equipment and techniques, continued to invest in model factories that were later sold to private interests. In effect, this constituted an indirect subsidy to domestic manufacturers. In the 1920s, when increased reliance was placed on joint ventures with foreign firms as sources of new technology, the government attempted to ensure that Japanese owners would retain (or obtain) control.

Moreover, the trajectory of Japanese industrialization, based upon the

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[1] Gus Ranis, "Industrial Sector Labor Absorption," EDCC, April 1973. See also Dilmus James, Uses Machinery and Economic Development, Michigan State Press, 1974.

[2] Kamekichi Takahashi, The Rise and Development of Japan's Modern Economy, Tokyo, Jiji Press, 1969, pp. 126-7.

accumulation of technical skills that has been reinforced by a strong commitment to education, especially the training of engineers, has led recently to industrial products of distinctly superior quality, design and performance. Although the contrast between imitation and innovation is often sharply drawn, it seems apparent that the cultivation of policies leading to successful imitation of foreign technologies also enables a country eventually to cross the threshold to technological innovation and a higher degree of industrial creativity. It is probably a mistake to believe that the skills required for successful borrowing and imitation are qualitatively drastically different from those required for innovation. Recent Japanese activity in such fields as robotics, composite materials, ceramics, fiber optics, fermentation processes, and various aspects of electronics, reveal convincingly that they have already crossed the threshold between imitation and innovation in a number of places.

It is apparent that the Japanese have committed large amounts of resources to productivity-increasing purposes, as evidenced by their emphasis on education and their high rates of capital formation. The commitment to education is an old one, and may well have been one of the most significant conditioning factors underlying Japan's rapid industrialization after the Meiji Restoration. During the Tokugawa period there is compelling evidence of substantial improvement in levels of literacy and education generally.[1] What has been less appreciated is that the Japanese economy has also been research-intensive for quite some time.

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[1] See the careful study by R.P. Dore, Education in Tokugawa Japan, University of California Press, Berkeley, 1965. Dore concludes: "However approximate our calculations of the diffusion of popular education must necessarily be, there can be no doubt that the literacy rate in Japan in 1870 was considerably higher than in most of the underdeveloped world today. It probably compared favorably even then with some contemporary European countries." (p. 291).

Certain aspects of its research activity have been highly significant. It has, in the past, been heavily concentrated in applied directions, although the basic research component has become more prominent in recent years. If one eliminates military spending from the comparison, it turns out that the Japanese have been devoting a larger share of their GNP to R&D for many years than has the United States. In fact, Japanese civilian R&D spending as a share of GNP has recently surpassed that of West Germany and is nor the highest of any of the western industrial economies.[1] Finally, the share of R&D that is privately financed is substantially higher in Japan than in other industrial economies.[2]

This suggest strongly that Japanese success in the mastery of new technologies has been heavily built upon strengthening incentives to private industry, rather than upon government-subsidized programs. The fact is that the Japanese government has contributed a smaller share of R&D expenditures, as

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[1] National Science Board, Science Indicators, e 1985 Report, U.S.F.P.O., 1985, Appendix table 1-4.

[2] This remains true even when the comparison is restricted to non-defense expenditures.

Govt. funding as a % of total R&D expenditures

	Total	Non-defense-related
Japan (1980)	25.8%	25.4%
United States (1980)	47.9	33.2
England (1978)	48.1	31.6
West Germany (1979)	46.8	43.6
France (1979)	51.1	37.9

Source: Dan Okimoto, "The Japanese Challenge in High Technology," in R. Landau and N. Rosenberg (eds.), The Positive Sum Strategy, National Academy Press, Washington, DC, 1986, p. 551.

compared to private industry, than have other industry countries.[1]

Although the Japanese success story is far from a story of total reliance upon free and unregulated market forces, it _is_ a story of government taking steps that are carefully calculated to strengthen private incentives, rather than to displace or override them. This may be one of the most important lessons of history for developing Asia.

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[1] for a valuable discussion of the role of the Japanese government in recent years, see Okimoto, _op. cit._, and, in the same volume, the paper by Masahiko Aoki, "The Macroeconomic Background for High-Tech Industrialization in Japan."