What Is A Critical Technology?

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1. INTRODUCTION: THE CRITICAL TECHNOLOGY MOVEMENT

Since the late 1980s the technology policy community has experienced what might be called a "critical technology" movement. The proponents of the movement share a common view that certain technologies have special properties that make them particularly important to national interests. The critical technology movement has been marked by the publication of more than one dozen major lists of such technologies, and has been symbolized by the creation of the Critical Technologies Institute and the establishment of the biennial National Critical Technologies Panel. This movement has produced numerous efforts to structure public policy around the organizing principle of critical technology. In the executive branch, the administration's technology policy for the U.S., announced in February of 1993, aims to accelerate the development of technologies that are believed to be "critical for long-term economic growth but not receiving adequate support from private firms."\(^1\) At the Justice Department, the Attorney General's office announced in early 1993 a new framework for counterintelligence called the National Security Threat List, which includes among the security risks to the nation "foreign intelligence activities directed at U.S. critical technologies as identified by the National Critical Technologies Panel."\(^2\)

On Capitol Hill, several bills have been introduced with the aim of organizing agency planning activities around critical technology lists. For instance, before leaving the Senate to become Treasury Secretary, Lloyd Bentsen sponsored legislation intended to establish an office in the International Trade Commission dedicated to monitoring the performance of U.S. industries in critical technologies, in light of the lists being prepared by the biennial panel.\(^3\) Senator Ernest Hollings introduced

\(^3\) U.S. Senate, S.2909, "Trade and Technology Competitiveness Act of 1992," 102nd Congress, 2nd Session, June 30, 1992. Bentsen's bill was not
legislation in the 102nd Congress that would have required federal agencies to spend at least 0.5 percent of their R&D budgets on projects aimed at promoting technologies listed as critical by the biennial Critical Technologies Panel. Critical technology legislation has been directed at the Departments of Commerce, Energy, and Defense.

In the space of a few years, "critical technology" has entered the conventional vocabulary of policy-makers in Washington. Yet the concept is plagued by a substantial problem: policy-makers have difficulty explaining precisely what it means. No commonly accepted definition exists, and there are no analytic constructs or theoretical models to indicate what makes certain technologies critical. The properties that differentiate critical from non-critical technologies have never been identified precisely.

Most discussions of critical technologies lack clarity about the meaning of the term. Many of the critical technology lists that have been sponsored by the Departments of Defense and Commerce, the private sector Council on Competitiveness, organizations representing the aerospace and computer industries, and the White House-organized National Critical Technologies Panel share this deficiency. The rationales associated with these committees' choices are extraordinarily varied. Stated criteria range from the potential contribution to human welfare and the quality of life, to the capacity of technology to improve the cost and reliability of weapons systems. Some criteria are therefore so broad and inclusive as to possess little meaning, while some obviously represent more narrowly defined agency missions or the interests of specific industries. The

taken up in the Senate, but the Commission has acted on its own to establish a related office.


For a summary, see: Genevieve J. Knezo, "Critical Technologies: Legislative and Executive Branch Activities," Congressional Research Service Report for Congress, 93-734SPR, August 5, 1993

See the appendix for a list of critical technology reports.

In Germany, efforts have been made to overcome some of these problems by using the Delphi method and other techniques to structure the identification of key technologies, but efforts at formalization such as this are by far the exception rather than the rule. See Harol Grupp, ed., Technologie am Beginn des 21. Jahrhunderts, Heidelberg: Physica-Verlag, Springer, 1993.
First National Critical Technology Panel's 1991 list was a decidedly mixed collection including end-user products (e.g., data storage and peripherals), applied science (e.g., molecular biology), process technologies (e.g., materials synthesis and processing), and systems technology (e.g., systems management technologies). As one participant in national critical technology list-making has commented privately, these lists can include everything from "physics to batteries." Critical technology is often defined only by example, a method which tends to conceal underlying judgments.

The implications of these problems of definition are more than semantic, since proposals for public policy often treat targeted critical technologies as if they were homogeneous enough that a particular policy instrument could be uniformly applicable. But these lists represent such a broad spectrum of scientific, technological, and commercial activities, that the returns from any given policy, such as directing 0.5 percent of an agency's R&D to all critical technologies, would vary dramatically across technologies. Moreover, definitional problems obscure the question of whether any public policy changes are appropriate at all. One of the major problems with the concept of critical technology is the often implicit premise that the private sector is not adequately producing the technology. Perhaps even more serious, it is sometimes assumed that formally achieving critical status is in itself sufficient to justify government action in a technology area—not necessarily a theoretically sound assumption. Selecting appropriate policies toward critical technologies requires clearer distinctions and a better definition of the term.

The purpose of this paper is to explore the concept of critical technology and to suggest a more meaningful interpretation of the concept. We proceed by first discussing the evolution of the term "critical," showing that it has been adopted in stages from another policy domain, strategic planning for raw materials. Many of the present conceptual problems with the term as applied to technology stem from borrowing the phrase from a domain where it is better suited. We then turn to the problem of improving the current conceptualization of "critical" in technology policy. We propose criteria for judging suitable interpretations of the term. Our criteria are intended to serve as tests
for establishing the utility of a definition of critical technology. We argue that a useful interpretation of the term should allow meaningful discrimination between types of technology, should be policy relevant, and should be likely to produce a reproducible list of technologies. Using these criteria, we then identify and evaluate four alternative definitions of critical technology that have come into common use. We label these: state-of-the-art technology; component of national self-sufficiency; rate-limiting factor; and, generic and pre-competitive technology. We find that only the last two of these four definitions meet our criteria for usefulness. Critical technology is best defined as either a rate-limiting factor in specific applications of interest, or as generic, pre-competitive technology useful in many applications.

With two improved interpretations of critical technology in view, we address ourselves in the final section of the paper to the question of whether criticality alone justifies public policy changes. Our conclusion is that it does not. As an organizing principle, critical technology may help policy-makers focus attention on technologies most likely to serve certain public purposes, but neither definition is by itself adequate to warrant policy responses by the federal government. Rather, we argue that the identification of critical technologies should be viewed as just one step in formulating policy proposals. There are potentially many opportunities for government action regarding critical technologies, but appropriate policies for promoting the development and assimilation of critical technology must be informed by a much wider range of judgments--for instance that there is systematic private under-investment in R&D in the technology, that barriers to the commercialization of technology are limiting the development of useful products, or that market failures are preventing the diffusion and assimilation of these technologies. We therefore conclude our discussion on a cautionary note, arguing that the concept of critical technology can be useful in the policy process only if it is both well defined and embedded in a larger theoretical and empirical context.
2. EVOLUTION OF THE TERM: FROM COPPER TO COMPUTERS

The etymology of "critical technology" helps explain how the term has come to be used by technology policy-makers and why its meaning is unclear. The phrase has been borrowed from another policy domain where its definition is more precise and its policy implications are better understood. The origins of the concept of critical entities lie in strategic planning. The term "critical" was used in the U.S. as early as the period between world wars as an adjunct to "strategic" in planning for war production and possible war-time interruption of militarily important raw materials such as copper and aluminum. Calls for stockpiling of such materials began after World War I. With war in Europe looming again, Congress passed the Strategic and Critical Materials Act in 1939. The law observed that "the natural resources of the United States in certain strategic and critical materials" were insufficient, and therefore the U.S. must adopt a policy "to decrease and prevent wherever possible a dangerous and costly dependence...on foreign nations for supplies of these materials in times of national emergency."

In this context, what were critical were those raw materials without which war-time and post-war economic production could not take place at desired levels. The designation was based on judgments about the foreign and domestic supply of raw materials and on projections of demand for these materials as an economic input. The policy implications were straightforward: alternative, secure sources of materials, combined with stockpiling and the development of alternatives, would be needed in sectors where demand could outstrip supply in case of war.

This meaning of critical continued to shape materials planning after World War II. In 1952, the President's Materials Policy Commission (the Paley Commission) recommended continued stockpiling of the 74 "critical materials" on the national stockpile list.\(^8\) Twenty years later, the


National Materials Policy Commission used the concept when reporting on the "federal stockpile of strategic and critical materials."\(^{10}\) By the mid-1970s, this interpretation of the term had entered standard English usage in the United States, and among the definitions of the word critical listed in Webster's Third New International Dictionary in 1976 was "essential for the conduct of war but available in short supply, as in critical materials."

Over the next ten years, use of the term critical underwent a transformation. In the defense community, the interpretation of critical grew to describe militarily important technology as well as materials. In 1984, the Defense Department released the Militarily Critical Technologies List, identifying thousands of technologies considered crucial to various defense systems. The following year, in amendments to the Export Administration Control Act, Congress authorized the Pentagon to control certain critical technologies. The meaning of critical when applied to technology was somewhat less precise than in its original natural resources context, but nonetheless conveyed the judgment that certain technologies were of greater military importance than others. By the mid-1980s, critical technology came to be understood as technology for which maintaining a secure domestic base was viewed as militarily important. Critical technologies were those that could confer a military advantage on the U.S., and which were not widely available to the U.S. or other nations in international markets.\(^{11}\)

In the same period, demands that technology contribute demonstrably to competitiveness and the nation's economic performance were increasing dramatically. The idea that certain advanced technologies were important to the U.S. because of their military significance was joined by the idea that certain technologies were strategically important in a purely economic sense; critical began to refer to commercial as well as military concerns.

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In 1987, for instance, the Department of Commerce produced a document analyzing ways to reduce barriers to the commercialization of technology, and this report came to be viewed as a commercial critical technology list. In 1989, the Pentagon's first annual Critical Technology Plan, which it prepared for Congress, included a number of dual-use technologies, such as microelectronics, fiber optics, biotechnology, and robotics. Growing attention to the concept of dual-use provided a bridge between the world of strictly militarily critical technologies and that of economically critical ones.

In the mid 1980s, increasing interest in technology that was of economic importance, combined with a growing concern with technologies relevant to health and welfare and environmental concerns, further expanded the application of the term critical. A report by the World Resources Institute on "environmentally critical technologies" is an example of this crossover of the term to other domains. By the early 1990's, when several major critical technology reports were released, the criteria for selecting technologies had extended to include contributions to the economy, quality of life, the environment, energy security, and so on. This crossover raises the question whether the resource-denial model long familiar to students of national strategic policy captures all the characteristics now held to be of policy interest.

The end of the Cold War, along with coincident changes in the global economic environment and the economic downturn in the U.S., consolidated the new, expanded application of the word critical. The observable fact of increasing competition from foreign producers in markets traditionally dominated by the U.S., combined with often tacit but nonetheless increasingly widely-held unease about the ability of the U.S. to be

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12Hill, op. cit.
14Indeed, part of the reason the definition of critical technology becomes so complex is that technology has the potential to affect not only the security and economic dimensions of public concern, but also domestic politics through displacement and redistribution of power, culture and the way individuals think about and operate within their society, and even perceptions about the desirability and likelihood of change.
competitive, has added a piquancy to the discussion of critical technology. In the new formulation, nearly any national goal can be found attached to the notion of criticality, but competitiveness has become the centerpiece. This juxtaposition of critical technology with another widely-used but rarely-defined term, "competitiveness," makes even more urgent the need for better understanding what criticality might mean.
3. DEFINING CRITICAL TECHNOLOGY

The crossover of critical technology terminology from strategic policy to domestic technology policy is still not entirely complete, because the concept remains somewhat unformed. A number of observers have commented on the need for a more useful definition of critical technology and a better understanding of its policy implications. The private sector Council on Competitiveness has noted that the U.S. needs to "move beyond simply making lists."\(^{15}\) Mogee notes that "in many cases the critical technologies are defined too broadly" to be useful for reorganizing R&D priorities and that critical technology lists "tend not to distinguish the different segments of U.S. industry nor recognize the difficulties in generalizing about the needs and interests of the U.S. industrial community."\(^{16}\) In its 1991 Critical Technologies Plan, the Defense Department points out that differences among critical technology lists are due to multiple definitions of the term.\(^{17}\) The Second National Critical Technologies Panel eschewed making a technical revision of its predecessor's list, observing that the more important task is establishing a "continuing effort to understand the relationship between technologies and the nation's economy."\(^{18}\)

CRITERIA FOR TESTING DEFINITIONS

What would a satisfactory definition of critical technology require? To avoid the problems that plague current lists of critical technology, a better definition would need to be explicit about assumptions, meaning, and relevance to policy discussions. It would be less ambiguous than existing definitions and rationales for the construction of technology lists. There


are at least three tests that a useful definition of critical technology should ideally be able to pass:

1. **Is it policy-relevant?** A definition should be useful for policy-makers. It should result in more than a technical taxonomy of technologies that leaves policy-makers asking, "Critical to what?". It should indicate where the points of potential policy intervention in the linked processes of R&D, commercialization, diffusion, and utilization of a given technology are to be found. The economic potential of some technologies, such as computer-integrated manufacturing, lie chiefly in solving problems of wider diffusion, while the benefits of other technologies, such as applied molecular biology, are likely to come from a focus on basic research.

2. **Is it discriminating?** A definition of critical technology should be useful in discriminating unequivocally between critical and non-critical technologies. It should not be so broad and inclusive that nearly any advanced technological process or product can qualify, and it should be as consistent as possible in level of aggregation and in clarity of classification, so as not to conflate without comment products with processes or science with technology. The criteria described by the First National Critical Technologies Panel as the source of its list of twenty-two technologies do not pass this test, for instance. The panel's use of nine rationales such as "ability to make strong contributions to health, human welfare, and the environment, both domestically and worldwide" admits many more technologies than are included on the panel's list.19

3. **Is it likely to yield reproducible results?** A definition should be sufficiently functional to enable the panels or agencies employing it to develop tests and methods that will prove functional, robust, and accessible to those not directly participating in the effort. On the basis of the criteria stated in most reports it is not possible to reconstruct the procedures used to select critical technologies.20 Statements of

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criteria do not lead unambiguously to the resulting choice of technologies. Many critical technology lists are indeed similar, containing several of the same technology groups, such as information technology and the supporting base of electronics, and advanced materials. But the similarity is the result of the constitution of the critical technology selection committees composed of experts in disparate fields, who must work at increasing levels of abstraction and aggregation to reach consensus among perspectives. All critical technology lists include electronics, for instance, but they do not concur about the relative criticality of advanced displays, active and passive sensors, packaging, or superconducting devices.

Reports also differ about whether major classes of technology are critical. Technologies over which expert panels tend to disagree include environmental and energy technologies, surface transportation technologies, and, in the case of the Defense Department, certain specialized technologies such as signature control and pulsed power technology. These differences reflect the interests of the institutions and industries represented by the individuals comprising the critical technology panels or of their convening organizations.

A better definition of critical technology should lead to a list of critical technologies in a reliable and reproducible way. The connection between the stated definition or criteria and the technologies chosen as critical should be transparent and should not conceal economic assumptions, institutional interests, and normative judgments.

It may be possible to consider a set of objective measures that might increase the likelihood of reproducibility of results. A panel might choose to consider as candidate technologies only those which exhibit high patenting activity, secondary citing of patents, or some other similarly quantifiable indicators of comparative advantage. Bear in mind, however, that identifying critical technologies should not become a mechanistic exercise in itself. Any definition of critical technology must still pass the first two tests.

We put forward these three criteria as tests which any useful definition of critical technology would ideally need to pass. These tests are intended as guideposts; for a definition to fail one or more tests is a
sign of serious trouble. However, these do not represent the entirety of
what one would need from a definition if developing a critical technology
list is to serve as a practical exercise from which policy decisions would
follow. As one example, it has been suggested above that an assessment of
criticality would ideally also incorporate an indication of where in the
technology development, diffusion, and utilization process public policy
instruments might be applied most usefully. These instruments may
therefore not necessarily be limited to allocation of federal R&D resources
but might also include measures to make potential users more receptive or
to accelerate the pace of testing. But a critical technologies panel or
selection process should also weigh the relative cost of employing such
measures.

In particular, costs and benefits associated with active government
intervention would need to be weighed by also assessing vulnerability to
imperfect information and the risks arising from two possible types of
error. Type I error would arise if, by leaving the balance of decision
making to the private sector, some promising area for development receives
insufficient investment or receives investment too late to capture an
otherwise available technological advantage. Type II error, on the other
hand, would occur if government undertakes an activist program of
encouraging and partially subsidizing R&D in a particular area and that
area then turns out to be far less promising than originally expected—
especially with respect to a dark horse technology that may come to
dominate the solutions originally sought in the area of priority.
Resources would be wasted, but more seriously, time, attention, effort, and
publicity are diverted from other areas. This consideration reinforces the
view that any exercise in selecting critical technologies must be done in
light of explicit goals which the technologies would help in achieving.
This point will be explored more fully below.

THE PROBLEM OF AGGREGATION

The three testing criteria can make more clear and perhaps help
overcome two common shortcomings of critical technology lists. These
shortcomings are the tendency toward over-aggregation and the related
problem of inconsistent level of aggregation. The evolution of critical
technology lists from military to commercial applications has entailed a broadening of technology categories. While Defense Department lists have generally identified technologies with sufficient specificity to relate directly to identifiable programs and projects, commercial critical technology lists have been much further abstracted from specific policy objectives or programs. They have represented technology groups at very high levels of aggregation.

As described above, critical technology panels made up of representatives of many agencies and industrial sectors have tended to aggregate technologies into a few major categories, in order to reach agreement about criticality in the absence of clear, unambiguous criteria. Microprocessors, RAM chips, and application specific integrated circuits, for instance, are therefore represented as "micro- and optoelectronics."

Highly aggregated technology lists are problematic for several reasons. They fail at least two tests for the usefulness of a critical technology definition. First, they are not discriminating, since labels such as "micro- and optoelectronics" or "information technology" refer to a variety of constituent technologies, some of which might be judged critical and some non-critical. Highly aggregated lists do not provide an exclusive mapping to specific technologies of interest, but rather provide only obvious signposts to collections of diverse technology.

Second, over-aggregated lists are not very policy relevant, because they obscure potentially important distinctions among technologies. The appropriateness of various policy instruments can vary within categories as broad as "surface transportation technologies" or "energy technologies," to cite two examples from the report of the First National Critical Technologies Panel. Rather than providing expert judgments about connections between technologies, policy goals, and policy instruments, over-aggregated critical technology lists provide little more than simple taxonomies of advanced technology.

Similarly, while there is no inherent virtue in developing lists of critical technologies at the same level of aggregation, there is value in ensuring that the naming of technologies will provide a basis for determining the practicality and desirability of public policy intervention. Keeping the three test criteria in open view when
constructing such lists will at least provide one means of checking that the level of disaggregation for any given technology will be sufficient to permit thinking about effective policy courses.

Ambiguity about definitions and criteria not only contributes to the problem of over-aggregation, but has led to the emergence of differing and sometimes incompatible interpretations of the phrase "critical technology." Some interpretations focus on the advanced, or "state-of-the-art" qualities of technology, and some on the desirability of domestic control over technology. Other interpretations are based on the belief in the intrinsic importance of certain applications of technologies in specific industries like aerospace or pharmaceuticals, and still others on the generic or emergent characteristics of technology. From these various interpretations we have distilled four distinct definitions. We use the three tests above as a basis for discussing and evaluating each.
4. FOUR ALTERNATIVE DEFINITIONS

1. Critical Technology as the State-of-the-Art

The simplest definition of critical technology is one that equates "critical" with "advanced." In this interpretation, critical technology is a synonym for high technology. The basis of this definition is the judgment that a critical technology represents the leading edge of development in a technical field.

In this interpretation, critical technology is of interest because it represents the state-of-the-art, and is therefore the locus of innovation and an indicator of an industry's or nation's level of technical sophistication. For instance, semiconductor memory might be judged critical under this definition for the following reason. Sophistication in the production of increasingly dense RAM's and control of the market for these products has been viewed as an important marker of Japanese technical prowess and of the loss of an important U.S. high-technology industry during the 1980s.

An example of this definition of critical technology can be found in the National Competitiveness Act now pending in the 103rd Congress. The bills (H.R. 820/S.4) contain, inter alia, provisions for critical technologies and manufacturing technology and extension. They use the terms "critical" and "advanced" as synonymous when referring to technologies promoted by the Advanced Technology Program at NIST, to proposed technology monitoring and advisory activities of the Commerce Department, and to other technology policy activities of the federal and state governments.

How useful is this definition, and how well can it inform technology policy? The definition is based on a technical judgment about the properties of the technology itself, without reference to applications or policy objectives. On the basis of this judgment the definition passes the second test for a useful definition of critical technology, because it depends on a distinction between the properties of being state-of-the-art and non-state-of-the-art. Intelligent vehicle and highway systems represent the state-of-the-art in automobile control and instrumentation
development, for example, while digital climate control and engine sensing, electronic ignition, and other widely used technologies no longer qualify.

In principle, distinctions between cutting edge and non-cutting edge technologies can be made, although obviously examples can be identified that straddle a line between the two and other practical problems tend to complicate distinctions. Because there can be a lag of several years between the proof of a state-of-the-art concept in a laboratory and the availability of the technology on the market, some care must be taken in identifying the stage of development at which a critical technology—understood this way—is of interest. Also, because there are hundreds of technical frontiers in various branches of technological development, a comprehensive mapping of critical and non-critical technologies using this definition would be extensive—much longer than the maximum of 30 that Congress has imposed on the National Critical Technologies Panels.

This definition also passes the third test of usefulness, reproducibility. In principle, independent groups of experts should arrive at similar judgments about the frontiers of development in various technical fields. While disagreement often exists about the most promising lines of research and about the best strategies for pushing the frontiers of technical development, enough agreement usually exists about the contour of those frontiers to make judgments reproducible.

But critical technology as "state-of-the-art" falls far short of passing the first test of usefulness, policy relevance. A definition based on level of technical advancement provides little useful information to policy-makers. This definition begs the question of what response, if any, government should have to the identification of critical technologies. Some state-of-the-art technologies are of tremendous economic importance, while others are esoteric enough to have little commercial relevance. Among economically important technologies, the potential role for government can vary greatly, depending on the nature of market failures, trade rules, and a host of other factors. This definition is best understood as a technical taxonomy rather than a policy-relevant distinction.
2. Critical Technology as a Component of National Self-Sufficiency

The first definition suffers from being too firmly rooted in technology without giving sufficient consideration to other factors. A second definition treats technology in a larger context. It views technologies as critical because they embody and confer vital capabilities: critical technologies are those for which the U.S. has an abiding interest in maintaining secure domestic sources.

This interpretation clearly originates in the resource-denial model outlined above in the discussion of critical materials and the defense resource base. In this case, however, technologies are deemed critical out of concern for ensuring security of the means for sustained economic growth and development--and in a complicated world economy, for "competitiveness."

All the variations on the theme of critical technology have running through them several common threads. One of these is an implicit, generalized concept of "control." The point of any exercise designed to identify critical technologies is to control or shape their access, development, and/or use in some way that serves the purpose of public policy. The essence of the second definition of critical technology is the concept of control.

But control is itself a multi-faceted concept. Depending upon the specifics of each technology, control could conceivably be derived from many qualities.\(^{21}\) Control can mean originality, since being the originator of technology is often believed to confer first-mover benefits. It can refer to exclusivity, because being a sole possessor or producer of technology could allow the capture of monopoly rents and other advantages. Control can involve reproducibility and the means to employ active measure of imitation, ensuring the ability to derive capabilities inherent in technology originated elsewhere. It can be associated with access, and the ability to procure the technology through purchase or by acquiring the means for producing it. That is, there may be a useful distinction between

\(^{21}\) Note that this too is an attempt to lay out in concrete terms another concept which remains inchoate and yet is raised to convey a powerful image in debates. The catalogue presented here is intended to be suggestive of the degrees of nuance that surround the concept of control. It is not complete, nor are the several senses of the word mutually exclusive.
acquisition which is a one-time event as opposed to a need to maintain an association with suppliers and commerce in the technology. Finally, control can also mean mastery in the sense of possessing the ability to develop or utilize the technology effectively.

These many possible meanings of control indicate how inadequate a base the concept provides for determining the critical nature of technologies. Many aspect of control are vague, and rest on little in the way either of theory or compelling practical arguments. For instance, first mover advantages have proven fleeting for U.S. innovators. On the other hand, in several cases the existence of foreign suppliers of technology and high technology goods has proven to be of benefit to U.S. interests rather than the specter raised in such works as The Japan That Can Say No. Japanese control of the DRAM market in the 1980's may well turn out to have been an unexpected boon to the U.S., because it left American firms to focus on the more design-intensive ASICs and microprocessors that are proving of vital importance to the evolution of the semiconductor and information technologies industries.

Problems with the idea of "controlling" commercial technologies cause this interpretation of critical technology to fail the second criterion for a satisfactory definition. It does not necessarily provide a useful distinction between critical and non-critical technologies outside the military context. An important reason for this failure is the problematic nature of the idea of commercial self-sufficiency in the increasingly interdependent global economy. Intra- and inter-firm flows of technology across national borders, in the form of the movement of physical artifacts as well as the electronic transfer of information render notions of self-sufficiency of the kind that drove critical materials policy somewhat irrelevant. International alliances between major U.S. firms and their Asian and European competitors for R&D and production make it increasingly difficult to define and control "U.S." technology.

Moreover, even in the traditional neo-classical economic view of trade across well-defined economic borders (where the pure system is characterized by free-trade, efficient markets, and phenomena of comparative advantage), this definition of critical technology is meaningless, since a nation's optimal economic strategy does not require it
to produce all the goods it consumes. However, the increasing visibility and stature of critiques of the neo-classical ideal view have given new vitality to the issue of control over technology.\textsuperscript{22} The critics make explicit recognition of market imperfections, political intrusions, and possibly new factors such as trade advantages nurtured by policy rather than stemming from natural endowments, economies of scope, and even new philosophies of manufacturing. Many would make a strong case for the policy relevance of this definition. The main force of this definition rests on the strength of its satisfying the first of our three criteria, even though the associated concepts are sometimes controversial.

But while the question of how public policy should treat control of technology is fairly raised, it is far from answered. Given the present state of knowledge, it is difficult to see a definition of critical technology based upon necessity for control which would pass the test of the third criterion and yield a methodology which could then be reproducibly applied. This is true even if one ignores the considerable problem of defining what constitutes U.S. control over technology in a world of increased globalization of markets and production and a consequent blurring of distinctions between foreign and domestic firms.

In the absence of further analysis, it is unlikely that adopting this second reading of criticality would lead to the increased clarity, utility, and ease of application that would make meaningful a concept of critical technology.

Before leaving this discussion entirely it is worthwhile to point out that when considering the list of meanings subsumed within a concept of control, the last one, mastery, has a different nuance than the others. Here, the image is less one of formal control in a legal sense than of control in function. It is tempting to discuss critical technology in terms of physical control while ignoring the fact that what ultimately matters is the use to which technology is put. It may be possible to achieve control in the most obvious sense while failing to pay attention to those factors which would yield mastery in the more limited one--that which

\textsuperscript{22}An influential example of this school is Laura D'Andrea Tyson's \textit{Who's Bashing Whom?}, Institute for International Economics, Washington, DC, 1992.
would allow U.S. industrial users to fully utilize the capacities embodied in their technical equipment. This consideration is quite consistent with recent scholarship in the area of innovation and technological change, which places emphasis on the intimate, context dependent, path dependent, and institution-dependent nature of technology. This view of control leads to a third possible definition of critical technology.

3. **Critical Technology as the Rate-Determining Factor for Specific Applications**

A third definition stems indirectly from the technology's function in making possible some desirable process or product. The principal difference between this definition and first two is that criticality is not inherent in the technology itself. The quality of criticality is derived from the importance of the outputs of the system of which the technology is a constituent part, as well as from the significance the technology has for enabling that system. (The terminology of a "rate-determining step" and its imagery derive from chemistry where in a multi-step chemical reaction there is usually one step which determines the rate of the overall reaction.)

This definition possesses several attractive properties. Its principal virtue is that it carries within it an explicit answer to the question: "Critical to what?" For example, is a technology under consideration critical to stronger aerospace exports or is it critical to increased employment in the auto industry? The Department of Defense has noted the need for viewing critical technology lists in context: "every critical technology requires an implicit modifier before it...to show 'critical to whom' or 'critical by what standards.'"\(^{23}\) The standard of obvious concern to this most mission-oriented of all federal agencies is to consider "the technologies most critical to ensuring the long term qualitative superiority of United States weapons systems."\(^{24}\) However, the DoD documents on critical technologies note that even within the defense arena, technologies critical for the Army differ from those critical for the Air Force and the Navy.

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\(^{24}\)Ibid, p. 4.
Similar variation exists among sectors of the economy in the criticality of specific technologies. What may be deemed a critical technology for one industry may in another fail to meet the standard set out by this definition. The designation of criticality must be preceded by a weighing of the importance of the material outputs or other benefits which issue from the processes employed by the industry.

Use of this derivative definition of critical technology helps link policy objectives to choice of technology. It makes technology policy fit more comfortably within the larger realm of public policy choice rather than, as is too often the case, being treated as a series of decisions raised by imperatives and opportunities driven solely by technical considerations. This definition acknowledges the important reality that critical technologies tend to have constituencies. A critical technology has connected with it an existing or prospective body of technical knowledge and related manufacturing, service, or system capacities around which a number of interests may coalesce in such a way as to form the basis for interest group activity. This definition, if applied in its fullest sense, serves to make these links clear.

By the same token, methods for assessing critical technologies which are derived from this definition could also take explicit cognizance of the problem that some policy objectives conflict where applied to the same industry simultaneously. This is perhaps best typified by the potential for dissonance between the desires to increase both employment and productivity. The case of flat panel displays, in which the interests of computer manufacturers are pitted against those of domestic display manufacturers, is another example. Applying this definition would force these frictions into the open at an early stage in the process.

This third, derivative, definition of critical technology is not without problems. It inherently relies upon the possibilities of finding meaningful methods of measurement that will permit qualification and perhaps even quantification of the importance of specific technologies to production processes. Of course, this assumption of the availability of means for measurement and assessment is inherent in the exercise of setting out to identify critical technologies in the first place. This point brings into focus a second potential limitation: this measure of merit is
more likely to be applied to technologies in their more well developed stages than to those which are more prospective or in the early teething stages. The purpose of identifying critical technologies is to detect points where policy may be needed to shape outcomes that enhance the ability to attain national goals. By its very nature this reading of criticality takes a narrow focus. This too is a function of the stage in the time course of development for a technology when this definition would come into play. It would not necessarily do well in identifying at an early stage technologies with potentially broad applicability.

There is one further consideration which is inherent in the notion of identifying and attaching importance to "critical" technologies but which is brought out clearly by the basis of this definition. Part of the nature of complex manufacturing processes is that addressing and ameliorating a bottleneck may have the unintentional effect of creating a new bottleneck in another step up or down the line. If we employ this definition in a myopic fashion, focusing on parts of systems rather than their wholes, does it then raise the risk of creating new bottlenecks in areas which are not privileged to receive scrutiny and fail to be designated as "critical"?

Despite these potential shortcomings, this approach has attractive prospects, and it nominally passes the three test criteria outlined in the previous section. It provides useful distinctions, for instance among specific techniques of applied molecular biology that are not critical to the aerospace industry, but are critical to the chemical and pharmaceutical industries. Yet some technologies in areas such as advanced materials and microelectronics may be found to be critical to many industries at once. This definition is policy relevant because it incorporates policy goals as its measures of merit, and it has the prospect of informing methods of assessment that will be reproducible.

It is clear, however, that in consideration of the problems listed above, while the third definition yields a useful measure of criticality in many prospective instances, it is not universally applicable. Important elements are left out. More is required by the fact that technologies may prove critical either in only a few applications or in many at once. This issue leads us to a fourth prospective definition of critical technology.
4. Critical Technology as Generic and Pre-competitive

A fourth definition of critical technology is based on the observation that at an early stage of development, some technologies can be judged useful for many applications. In this interpretation, technologies are critical because development efforts are believed likely to produce a wide array of returns not tied to any specific product application. These technologies have synergistic or catalytic effects on other technologies, and are at an early enough stage of development to be pre-commercial in nature. Obviously not all technologies with broad applications and synergistic effects, such as computer systems, are pre-competitive.

Some generic and pre-competitive technologies are those for which specific applications can be identified, such as advanced materials technology in the automotive, aerospace, semiconductor, and sporting goods industries. These represent technologies qualifying as critical according to the third definition above, with the added property of having multiple applications and being non-proprietary in nature. Other generic and pre-competitive technologies might qualify on the belief that their effects and applications are far reaching even though not identifiable in a specific way, such as in the case of protein engineering.

The Advanced Technology Program (ATP) at NIST uses criteria for selecting award winners that is broadly consistent with this definition of critical technologies. ATP provides grants to firms for the development of technology that is beyond basic research and prior to the start of product development and that holds the potential for many end-use applications. Examples include development of nanocrystalline ceramics, X-ray lithography techniques, and thin-film superconductor manufacturing equipment.²⁵

This definition of critical technology passes all three tests for usefulness. It is discriminating in that it provides distinctions along two dimensions: between pre-competitive and proprietary technologies, and between those of broader and narrower applicability. While these distinctions are not always pure in practice, they provide a meaningful standard for discriminating among critical and non-critical technologies.

This definition is also policy-relevant. It provides a well-defined focus for policy-making efforts aimed at promoting specific types of technology. The case of ATP, along with SEMATECH, which develops technology applicable to the products of all consortia members, is an example of how this definition may serve as a tool for identifying areas which might prove useful objects for focusing public policy concerns. Note, however, that the exercise of this definition, or any other, to identify potentially critical technologies is not sufficient in itself to trigger an automatic policy response. It merely serves as a means for checking off one of a series of factors which must be examined in the policy formulation process. This point will be discussed further below.

Reproducibility is perhaps the most difficult test for this definition to pass, because there are many pre-competitive technologies with the potential for broad effects, so no list of limited length can be inclusive. For example, in its first three competitions, the ATP program funded a total of 60 projects that qualify according to this definition, and that number will continue to grow. There is no a priori reason why two short lists of critical technologies defined this way would be the same, unless individual technologies are aggregated into major categories--which sacrifices policy relevance. But a degree of reproducibility is possible in principle if bounds are placed on the selection of technologies. Bounds may reflect policy choices, such as significance to a set of political objectives like a cleaner environment, or they may reflect technical bounds, such as technologies in major categories such as information technology or biotechnology.
5. CONCLUSION: USING THE CRITICAL TECHNOLOGY CONCEPT

Of the four definitions of critical technology, only the last two stand up to close scrutiny. By nominally passing all three tests for usefulness, these interpretations are policy-relevant, discriminate among types of technology, and are likely to lead to reproducible results. (While the third definition passes these tests somewhat more easily than the fourth, to embrace only this definition would be to miss a potentially important aspect of how technology development affects society.) Both definitions embody ideas already in use by policy-makers, and provide greater clarity and internal consistency than the vague criteria on which many critical technology lists have been based in the past.

These definitions lend themselves to different policy applications. As rate-determining-factor for specific applications, the critical technology concept addresses public policy problems where the goal is the promotion of sectoral or industry-specific economic health. It focuses attention on the redress of selected market failures or specific political demands. These considerations may occur at any stage in the R&D, diffusion and assimilation process. Understood this way, government support of critical technologies can include a range of policy instruments, from the funding of basic research to manufacturing-extension activities. It can be directed at commercial activities, in the form of trade rules and government procurement policy, as well as at pre-competitive activities.

As generic and pre-competitive technology, the concept of critical technology has somewhat different policy implications, because it is addressed to broad, economy-wide applications. Government support of generic and pre-competitive technologies is based on the belief that these technologies are part of the nation's commercial industrial base, and does not require the selection of specific industries or sectors for support. This definition suggests the application of policy instruments aimed at pre-competitive stages of the R&D process, such as cooperative research agreements with the national laboratories, facilitation of consortium formation, and the funding of corporate development activities that have not yet reached proprietary stages.
Both interpretations reveal that criticality is not a property inherent solely in technologies themselves, but is partly a function of both the role of technology in economic processes and of the objectives of policy-makers. One implication of this inquiry is that meaningful choices about which technologies are critical can not be entirely separated from political judgments about what the government ought to do to promote economic health. Identifying critical technologies requires prior judgments about how national economic health is to be pursued—whether through the selective support of specific commercial activities or through policies that are broader in scope and non-selective. It should be stressed that prior judgments such as this are necessarily political in nature. They may be informed by analysis and economic theory, but also involve normative decisions about how best to define and promote the public good. This exploration indicates that a nation's "critical technology base" is really a heterogeneous collection of entities. The properties and importance to policy-makers of individual components can be obscured by simple, highly-aggregated lists based on vague criteria that mask trade-offs among policy goals and objectives.

The search for a bounded list of critical technologies, which has been the organizing principle of most efforts, may actually be misguided. It is possible that rather than serving as the basis for "top-ten" lists of technologies, the concept of criticality may be more useful if understood as a property that can be identified in many technologies—many more than can be listed in brief annual reports. Viewed this way, the value of the concept derives not from the reduction of many technological activities and potentials to a prioritized and necessarily facile list, but from its power to serve as a tool to distinguish among technologies based on their relevance to policy goals and to indicate links between innovation, economic prosperity, and public policy. It would be more valuable in many instances to direct efforts toward better elucidating the nature of these links than to generating lists themselves.

One of the benefits of an approach which focuses on goals is that the discussion is broadened beyond technologies to consider capabilities for meeting specific objectives. Mastery or control over specific technologies will certainly be among the most powerful means for attaining specific
ends. But depending upon the particular goals that are chosen, policymakers should not be blinded to other avenues to achieving goals. Technological routes to economic objectives are not necessarily the most desirable.

One of the most important problems associated with the critical technology movement has been the temptation to assume that the identification of a technology as critical implies that a government response is called for. This temptation is evident in policy directives based only on critical technology lists—such as R&D funding mandates directed toward the National Critical Technology Panel's selections. The central conclusion of our inquiry speaks to this problem: neither of our two useful definitions of critical is itself adequate to warrant public policy responses. While criticality might be construed as a necessary condition for government action, it is clearly not sufficient.\textsuperscript{26}

Meaningful interpretations of the concept do not alone indicate that markets are providing an inadequate supply of the technology to meet national goals. Nor, for instance, do they indicate that government efforts to increase the volume of R&D undertaken (through funding programs) will have any effect on the rate at which the technology is commercialized and diffused. Public policy must be informed by a much wider set of assessments of market failures and the possibility of correcting them, not only by judgments that a technology is relevant to a policy goal. The identification of critical technologies is only one step in understanding the conditions under which technology is diffused, managed, and employed, and of identifying appropriate government roles in shaping those conditions.

Other cautionary notes are appropriate in closing, since a number of potential obstacles still surround the critical technology concept. One possibility is that by the time a technology is generally held to be critical, meaningful opportunities for policy action may have passed. Increasingly, the pace of commercial innovation exceeds the capacity of political institutions to respond in a timely way. This problem is

exacerbated by the tendency to treat the identification of critical
technologies as a periodic exercise conducted by central authorities. An
important advantage of treating the critical technologies concept primarily
as a source of working distinctions that can inform public and private
decision-making in real time is greater responsiveness.

It must also be recognized that the antecedents of the impulse to
define critical technologies are partially psychological. When faced with
the uncertainty inherent both in the processes of technological change and
in their effects, it is natural to peer into the future in the hope of
perhaps catching a glimpse of new certainties. At the same time, it is
also natural to try to gain a measure of control by imposing, even if only
unconsciously, a preferred structure on the future. Often it proves
difficult to prevent an objective attempt to project into the future from
lapsing into an exercise with implicitly causal expectations, as if the act
of forecasting and preparing will in itself increase the chances of a
desired future actually transpiring. There is a risk that this activist,
unintentionally normative attitude toward the future will distort the
exercise of technology forecasting and assessment.

The comfort that comes from having given a recognizable face to the
future can lead to what has been called the "illusion of control." This
illusion is especially tempting in areas of policy analysis characterized
by great complexity in their underlying systems, as is especially the case
in technology policy. Some of the concern over critical technologies and
the desire to identify them and frame policy around them may reflect
anxiety about technological change and the uncertainty and risk associated
with the future. This apprehension is understandable and inherent in the
process—but not every response to it is valid or opportune as a driver of
policy.

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27 The term was first used by Gary B. Silberstein of the University of
California, Santa Cruz.
A. CRITICAL TECHNOLOGY REPORTS


