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ABSTRACT

This paper reflects on the relevance of "systems-theoretic" approaches to the interdependent policy issues relating to the dynamics of science, technology and innovation and their relationship to economic growth. Considering the approach that characterizes much of the current economics literature's treatment of technology and growth policies, we pose the critical question: what kind of systems paradigm is likely to prove particularly fruitful in that particular problem-domain? Evolutionary, neo-Schumpeterian, and complex system dynamics approaches are conceptually attractive, and we examine their respective virtues and limitations. Both qualities are readily visible when one tries to connect systems-relevant research with practical policy-making in this field.

Keywords: science and technology policy, innovation policy, R&D subsidies, IPR, systems research, economic growth theory, complementarities, positive feedbacks, complexity, market failures, policy implementation failures

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1. Introduction

Advances in research on the political economy of science and technology policy, and contributions to the sociology of scientific knowledge and our understanding of the "social shaping" of technologies", have attracted increasing notice in recent years[1], raising critical questions about the social desirability of the directions in which scientific and technological research and development are channeled in modern societies (see for instance Callon et al., 2001, Ripp, 2003). Economic research addressing science and technology policy matters, however, has remained largely preoccupied with something else. Interest in R&D and innovation policy has certainly increased recently among academic economists,[2] even those predisposed to follow the discipline's "mainstream" (Helpman, 1998, Jaffe et al., 2004, Romer, 2001, Klette and Moen, 2000). Undoubtedly, this development reflects the widely shared perception that the higher levels and rates of growth enjoyed by some national economies are attributable to the greater success of those countries in exploiting emerging technological opportunities. Most of the economists drawn to this area are intrigued by the possibility that the positive results observed can be traced to effective policy programs, that is to say, to programs whose comparative effectiveness stemmed from a correct sequencing of the stimuli given to a proper mix of exploratory and commercially-oriented R&D, and to private sector investments in technology-embodying capital and human resource training (Mohnen and Roller, 2001, Trajtenberg, 2002).

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[1] See, for example, the rising membership and broadening activities of the European Association for the Study of Science and Technology and the US Society for the Study of Science and Society. The European Commission's "Science in Society" theme for FP7 (2007-2013) includes funding support for "multi-disciplinary research addressing science-society interactions as a system," and projects that combine "Science in Society expertise with the science policy design and implementation belonging to other specific S&T fields." [See http://ec.europa.eu/research/science-society/index.cfm?fuseaction=public.topic&id=76]. The US National Science Foundation's Social, Behavioral and Economics (SBE) Directorate created a "Science, Technology and Society" (STS) program, including two programmatic areas that currently focus on Social Studies of Science, Engineering and Technology (SSS), and Studies of Policy, Science, Engineering and Technology (SPS). [See http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=5324&org=SES&from=home].

[2] The National Bureau of Economic Research Working Paper Series is a major outlet for "mainstream" academic research on these subjects, although hardly one that is comprehensive. A Google search (on 11.10.08) yieilded 17,200 hits for "NBER Working Papers" +"R&D",; and 2,730 hits for. "NBER Working Papers" + "Economics of Innovation." The Centre for Economic Policy Research Discussion Papers occupy a comparable position for English language research: Google searches for these subject areas, substituting "CEPR Discussion Papers" yielded 12,900 hits for "R&D", and 2,330 for "Economics of Innovation". Science technology policy gets relative less attention in the NBER publications than it receives from academics in the UK and Europe who contribute to the CEPR programs: searches for "Science and Technology Policy" yielded 1,070 in the former case, and 1,110 in the latter.

For the most part, economic contributions to the literature eschew explicit discussion of the allocation of resources for different kinds of discoveries and inventions, or the choices among alternative ways in which new technological capabilities might be deployed. Instead, the analysis conceptualizes “research activities” as absorbing a homogeneous flow of the economy’s investment, and giving rise, in turn, to an uncertain stream of additions to the stock of generic knowledge. The latter, conveniently, is assumed to be quite malleable in the sense that it can be particularized as an array of specific technological capabilities that, under the right economic conditions, can generate innovations yielding lower cost or higher quality new goods and services, or possibly both. Moreover, the information yielded by research can enlarge the stock of (generic) knowledge and specific technical capabilities, upon which future research activities will be able to draw. Articulating these dynamics, and the positive feedbacks that contribute to sustaining the accumulation of a scientific and technical knowledge-base for the growth process, while ignoring the particulars of the differentiated “research outputs”, is a nice finesse in this conceptual scheme. It is accomplished by the “homogenizing” device of associating the consequences of the heterogeneous informational novelties with increases in the overall efficiency of aggregate input use in the economy at large, or, alternatively, in major industrial sectors.

One further step serves to carry the analysis from the “positive” to the “normative” realm, a step that avoids one becoming enmeshed in choices among concrete societal options by instead considering the most generic class of policy problems. This is the issue of whether the right level of investment is being allocated to the production and dissemination of new research results – i.e. whether the institutionalized and informal processes of information and knowledge generation are optimal, or should be optimized by public policy measures, so that they yield the desired long-run rate of technological innovation and productivity growth.[3]

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[3] - Following common usage in economics, the term “information” will be used here in referring to “knowledge” that has been reduced and converted into messages that can be easily communicated among decision agents – a process that entails a measure of “codification”, in the sense of restatement in socially intelligent and hence communicable “code”. Transformation of knowledge into information is a necessary condition for the exchange of knowledge as a commodity. Both processes of production and distribution of knowledge and information are central topics for technology policy.

Rather than being treated in isolation as distinct and separate topics,[4] science, technology and innovation are brought together by this scheme for consideration within a dynamic general equilibrium context - that being the characteristic mode of analysis in modern macroeconomic growth theory. The resulting research agenda's simplicity is breathtaking -- breathtakingly elegant, indeed, for those being introduced to the logic of "mainstream" economics. Certainly, the coherence imparted by this schema to the analysis of diverse policy questions is impressive, and, for most economists at least, it is undeniably "good to teach".

To launch a debate on the esthetics of theory, however, is not the intention here; the issue is not "theory for theory's sake", but, instead, theory and empirical research for the sake of informed and effective policy practice. Can workable science, technology and innovation policies be designed and evaluated in a "systems-theoretic" framework? Should one expect the dynamic general equilibrium framework, which has been the dominant paradigm for growth theory, to provide appropriate guidance for policy researchers confronting realities that constitute compelling arguments for pro-active government policies? What direction does it offer in selecting and designing programs to affect the production, distribution and utilization of scientific and technical knowledge and information Some researchers (e.g. Nelson, 2005) have expressed serious intellectual doubts on this score, arguing that the logic of competitive general equilibrium analysis rests upon empirical suppositions that, were they valid, would be seen by many economists to vitiate the case for any public intervention in the working of markets.

For governments to attempt to affect resource allocation by pervasive and sustained policy actions would, in that context, need to be "justified" on the ground that private incentives provided by "free markets" systematically would perform poorly, indeed more poorly than the prescribed interventions. But then, the argument goes, if not competitive general equilibrium dynamics, what sort of "theory" could serve to guide the prescription of remedies when markets fail?

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[4] Treatment of these topics as sub-specialities within a research domain labeled "the economics of science, technology and innovation" would be expected, were such a field fully recognized by the Anglo-Saxon mainstream literature. But no such "field" with appended "subfields" can be found in the *Journal of Economic Literature*'s widely used classification scheme. That omission poses an interesting anomaly for students of the sociology of science. An explanation might be found by examining an associated puzzle: the leading graduate economics programs in the U.S., and those patterned on them in other places, do not treat "the economics of science and technology" as an area of specialization for doctoral students, even though graduate courses on that subject are offered by some of those departments. A quite different situation prevails at many universities in Europe.

The increasing awareness of the intimate and multiple connections of technological change and innovation with advances in science, on the one hand, and the set of socio-economic institutions operating in a given context, on the other, encourages the conceptualization of "science, technology, innovation and growth systems" (STIGS) as appropriate subjects for policy-oriented research. Alternative conceptual frameworks, including those more amenable to evolutionary analysis of the dynamics of complex systems, may readily spring to mind here.

"Systems-thinking" in its broad sense is comprehensive enough to embrace both the style of general equilibrium analysis that is familiar in mainstream economics, and more recent advances in systems theory that during the past two decades been percolating into economic analysis from physics, chemistry and biology, and well as the ecological sciences. After all, the English word "system" comes from the Greek *sustema,* which stood for reunion, conjunction or assembly – the whole created by bringing together a multiplicity of individually identifiable interacting parts.[5] Modern systems research and 'systemics" embraces the "holistic" rather than the reductionist approaches to developing logical, mathematical, engineering and philosophical paradigms, or frameworks to study the dynamics of physical, technological, biological, social, and cognitive systems. For economists attracted to this still heterodox perspective, the departure from the conventional viewpoint of general equilibrium analysis lies in the assumptions that it allows one to entertain regarding the nature of the interactions among the constituent elements (the "agents') of the economic system. The kinds of complementarities among some of the constituent elements of the economy -- precisely the feature that Simon (1962) saw as differentiating the architecture and dynamics of a complex system from that of a simple unorganized collection of elements – create pathways for positive feedbacks.[6] Positive feedback

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[5] On the intellectual roots and modern development of "systems research" and its relationship to cybernetics and "complexity theory", see François (1999). Among prominent economists, Simon (1962) was a pioneering contributor to the modern theoretical treatment of complex systems. The application of system-theoretio approaches to science and technology policymaking has been discussed by several scholars, notably in Sagesti's (1972) early monograph which applied it to design of policies for developing economies. For further characterization of modern development in "systems thinking", and some useful references, one may consult the Wikipedia entries at: http://en.wikipedia.org/wiki/Systems_science

[6] The term "complex system" has no standard meaning, and is used in many different ways. Some writers use it to signify deterministic systems with chaotic dynamics; others refer to cellular automata, disordered many-body systems, "neural" networks, adaptive algorithms, pattern forming systems, and still others. Daniel Stein (1989: p. xiv), introducing the Santa Fe Institutute series of Lectures *in Sciences of Complexity* observes that complex systems share the property of exhibiting surprising and unexpected behavior that somehow seems to be a property of the system as a whole and cannot be inferred or deduced by examining the behaviors of it component elements in

processes are the source of dynamic instabilities that give rise, in turn, to the existence in the system of multiple "attractors" or equilibrium configurations. In so-called "composite" (or "quasi" -) systems that are open in some respects (not strongly "integrated"), tha massive absorption of energy can drive the system sufficiently far from equilibrium for positive feedbacks to induce oscillations of ever-increasing amplitude until a critical threshold of instability is crossed. As the pioneering work by[7] Prigogine (1955) established, at such points it is possible for the system to undergo bifurcations towards higher levels complexity, through the emergence of new, ordered (and hence dissapative) configurations that become stabilized at higher levels of entropy. Extensions of this conceptualization to a view of economic development processes as involving *qualitative* transformations -- that is to say, organizational changes marked by the emergence of structures of greater complexity, and not mere quantitative replication that expands an unaltered configuration of the system – has exerted a strong appeal, drawing some economists to explore evolutionary economic paradigms.[8] For others, the existence of micro-economic structures and relationships among agents in the economy that give rise to positive feedbacks (in advanced and developing economies alike) are grounds simply for expecting that transient historical circumstances can play a role in selecting among the multiplicity of potential configurations that may become stabilized in a non-ergodic system (David 2005, 2007).

Certainly models of the economy as a complex system might commend themselves for adoption as vehicles of analysis that are logically more consistent with the pursuit of enlightened public policies aimed at managing elements of a STIG system beset by conditions of imperfect information, pervasive self-reinforcing externalities, and generate barriers to competitive entry. Such conditions are likely to produce markets outcomes that chronically remain substantially less

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isolation. So, a common characteristic of "complexity research" is a synthetic. "Gestalt", approach, as opposed to reductionism.

[7] For subsequent generalizations and extension to social processes, see Prigogine (1980), and Prigogine and Stengers (1984). See Haken (1978) on self-organizing systems and 'synergetics"; Bak (1996) on self-organized criticality and bifurcations in "composite" systems.

[8] See, e.g., Arthur et al. (1987), and Arthur (1994). For evolutionary theorizing on economic growth, see Silverberg and Verspargen (2005). Exemplifying such processes in formal models, and exploring them by stochastic simulation methods has been one fruitful line of research that has been productive of insights into industrial dynamics, e.g., the use of "history friendly modeling" by Malerba and Osenigo (2000), and Malerba, Nelson et.al (2006).. Pursuing at less formalized evolutionary approach to the dynamics of organizational ecologies, Metcalfe (2007), nonetheless arrives at important insights that are more explicitly focused on providing guidance of science, technology and innovation policy.

than socially efficient in a static resource allocation sense, but also can faill to realize potentialities for innovation, growth and secular improvements in economic welfare. The important question that then presents itself is whether, within such a paradigm, it really would be feasible to design and evaluate appropriate policy interventions. In this paper we revisit a number of favorite topics in that spirit, and discusses some implications of adopting a larger systems perspective for policy analysis.

This paper has also been written to stimulate some multi-disciplinary discussion. Much of what we wish to communicate draws upon general ideas and insights from systems theory – a notably interdisciplinary field, whose founders brought together theoretical concepts and principles from ontology, philosophy of science, physics, biology and engineering. System-theory research has since found its way into diverse research domains, including many of the social sciences. As we are concerned with "technology policy", we recognize the virtues of a systems approach to technical change and innovation. Such an approach helps to highlight and capture several characteristics of the process of innovation and technological change that are of direct relevance to technology policy. These characteristics involve: i) the multi-directional links at the same point in time between the stages of technological change; ii) the cumulative processes over time leading to feedbacks and lock-in effects; iii) the dependence of technological change upon knowledge and the assimilation of information through learning; iv) the unique character of the details of the development path and diffusion process for each innovation; and v) the systemic and interdependent nature of the process of technological change. The implications of these characteristics for technology policy; that is to say, of a *historical* systems approach to technological change and innovation, are the main subject of discussion in the following sections.

Our discussion of these difficult questions follows a line of argument that is set out in the next five sections. Section 2 presents an overview of STIG policy that integrates the market failure rationale for policy within a broader system perspective. The market failure rationale for technology policy rooted in Nelson (1959) and Arrow (1962) has been more recently extended by considering the implications of innovation complementarities, coordination and system failures, and the economics of the path-dependent evolution of technologies and institutions. Each of these conceptual developments involves a certain articulation of the market failure approach in a larger system perspective, and a corresponding search for appropriate policy tools and instruments.

Section 3 opens the toolbox to discuss the proposition that a "correct" policy needs instruments that are neutral and nonspecific with respect to technologies and firms, and to assess the extent to which the STIG perspective provides some economic rationale for *non-neutral* policy interventions. That perspective is widened in Section 4, which examines critical aspects of the interdependence between STIG-policy and other classes of economic policy concerned with human capital formation, macroeconomic performance, effective competition, the efficiency and flexibility of labor markets, and the stability and responsiveness of financial institutions. The potential weakness of any narrowly focused technology policy is likely to materialize when the complementary components of the whole economic system have not been considered.

Section 5 then takes up the question of the practicalities and costs of actual policy interventions. Understanding the basic principles of market failures does not carry one very far in terms of deriving practical recommendations about the construction of effective policy "interventions" that must be executed in real time. The practical difficulties of designing "interventions" for a system of such complexity pose formidable challenges because at least some among the conditions that call for government policy interventions also imply that important aspects of the system's behavior may be "emergent properties" that cannot be reliably deduced from a knowledge of the properties of its constituent parts. The paper concludes with a few cautionary reminders of the political hazards that await policy researchers and practitioners who suggest that their work on large and complex systems should be evaluated on the basis of observed policy "outcomes".

2. Toward a larger dynamic system perspective for policy analysis

The modern economic case for policy intervention in this area (as in others) rests first on establishing persuasive grounds for concluding that, in its absence, the outcomes would be suboptimal. That step, which is necessary but not quite sufficient for practical policy purposes, is rooted in the now classical formal statements about the problematic functioning of competitive market processes when they deal with information, itself both an input and an output of "research", as an economic commodity.

2.1 The market failure rationale for policy: public goods and "appropriability problems"

Modern economists have followed Nelson (1959) and Arrow (1962) in arguing that the potential value of an idea to any individual buyer generally would not match its value to the social multitude, since the latter would be the *sum* of the incremental benefits that members of society derived from their individual use of the idea. Those private benefits, however, will not readily be revealed in a willingness to pay on the part of everyone who would gain thereby; once a new bit of knowledge is revealed by its discoverer(s), some benefits will instantly spill over to others, who are therefore able to share in its possession at little incremental cost. Why should they then offer to bear any of the initial sunk costs incurred in bringing the original thought to fruition?

Commodities that allow themselves to be used simultaneously for the benefit of a number of agents, are sometimes described as being non-rival in use (see Romer, 1990), or has having the property of infinite expansibility or the ability to generate "intertemporal knowledge spillovers" (see, e.g., Dasgupta and David, 1994; Aghion and Howitt, 1998). This characteristic is an extreme form of decreasing marginal costs as the scale of use is increased: although the cost of the first use of new knowledge or information may be large, in that it includes the cost of its generation, further instances of its use impose a negligibly small incremental cost. It sometimes is thought a defect of this formulation that it ignores the costs of training potential users to be able to find and grasp the import of information, or to know what to do with it. But, although it is correct to recognize that developing the human capability to make use of knowledge and information are processes that entail fixed costs, the existence of the latter does not vitiate the proposition that reuse of the information will neither deplete it nor impose significant further (marginal) costs. A second peculiar property of knowledge or information that should be underscored here is the difficulty and cost entailed in trying to retain exclusive possession of them while, at the same time, putting them to use. While it is possible to keep secret a fresh bit of information or a new knowledge, the production of visible results that were not otherwise achievable will disclose (at very least) that a method exists for obtaining that effect.

The dual properties of non-rival usage and costly exclusion of others from possession define what economists mean when they speak of public goods. While the term has become familiar, confusion lingers around its meaning and implications. It does not imply that such commodities cannot be privately supplied, nor does it mean that a government agency should or must produce it, nor does it identify "public goods" with *res publica*, the set of things that remain in "the public domain". What does follow from the nature of public goods is the proposition that *competitive* market processes will not do an efficient (i.e. close to the social optimum) job of allocating resources for their production and distribution. Where such markets yield efficient resource allocations, they do so because the incremental costs and benefits of using a commodity are assigned to the users. In the case of public goods, however, such assignments are not automatic and they are especially difficult to arrange under conditions of competition. The disclosure of even a commodity's general nature and significance (let alone its exact specifications) to a purchaser consummating a market transaction can yield valuable transactional spillovers to potential purchasers, who are free to then walk away. Complex conditional provisions in the contracts and a considerable measure of trust are required for successfully "marketing an idea", and both of these are far from costless to arrange, especially in "arms length negotiations" among parties that do not have symmetrical access to all the pertinent information. Contracting for the creation of information goods the specifications of which may be stipulated but which do not yet exist is fraught with still greater risks; and, *a fortiori*, fundamental uncertainties surround transactional arrangements involving efforts to produce truly novel discoveries and inventions. This leads to the conclusion that the findings of scientific research, being new information, could be seriously undervalued were they sold directly through perfectly competitive markets, and the latter would therefore fail to provide sufficient incentives to elicit a socially desirable level of investment in their production.

The foregoing describes what has come to be referred to as the "appropriability problem", the existence of which is invoked in the mainstream economics literature as the primary rationale for government interventions in the area of scientific and technological research by means of various public policy instruments (Nelson, 1959, Arrow, 1962).[10]

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[10] Arrow (1962) points out that in regard to "basic" or exploratory scientific research, uncertainty poses special obstacles to the mobilization of private profit-seeking investment, which often are compounded by the long-time

Two other types of market failures are referred to in the literature as contributing to the diagnosis of a chronic condition of under-investment in scientific and technological research by the private sector. Firstly, the value of basic research is more conjectural than that of applied research and is therefore more likely to be undervalued by private firms and individuals. They are likely to be more risk adverse than they would be if acting collectively through the government and so may avoid undertaking basic research to any large extent because of its greater uncertainty. Basic research involves also a longer gestation lag than applied research. If private rates of discount exceed social rates, either because of myopa or because of imperfect capital markets, there is a case for the provision of public assistance to basic research. Secondly, imperfections in the capital market that leave researchers asset-constrained, particularly when facing the likelihood that an exploratory project will have an extended duration and a long wait before results can be exploited commercially, is a source of "R&D market failure" *per se*, when the researcher, the innovator and the financier are distinct entities. Small and start up fims face a higher cost of capital than their larger competitors. There often is a wedge between the rate of return required by an entrepreneur investing his or her own funds and that required by external investors. Unless an innovator is already wealthy, some innovations will fail to be provided purely because the cost of external capital is too high – even when innovators would pass the private rate of return (or payoff period) hurdles were funds to be available at normal interest rates.

This is the standard set of problems that calls for some form of policy response. A number of principles are advanced as guidance for such interventions, some of which turn out to be less compelling than might appear at first sight.

2.2 "Open science" and proprietary research: wonderful but flawed organizational regimes

Part of the conventional market failure justification offered for government intervention in the sphere of scientific and technological research and development recognizes a difference

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horizons needed before the inquiry bears fruit in practical applications. By comparison, applied industrial R&D projects are undertaken when the distribution of costs, and the waiting time before payoffs can be realized is much more compact. But uncertainties as to what one will discover, are hence about the match between those eventual research results and the capabilities the entity that has conducted the exploration to commercially exploit the findings contributes to lowering expectations the magnitude of the benefit that it will be able to privately appropriate.

between exploratory or “fundamental” or “basic research”, on the one hand, and “applied” or “commercially-oriented” R&D, on the other. The special need to subsidize the former has been found in its greater level of uncertainty, and the longer time horizons over which research programs of that kind generally need to be sustained. This line of argument, however, does not adequately account for the existence of two quite different organizational and incentive mechanisms that government support maintains in order to provide economic support for research activities. More recent institutional analysis associated with the so-called “new economics of science” has offered a functionalist explanation for the “open” part of the institutional complex of modern science, which traditionally was (and in many countries still is) closely associated with the conduct of research in public institutes and universities (see Dasgupta and David, 1994;David 2003).

The modern rationale for public policies supporting “open science” focuses on the economic and social efficiency aspects of rapid and complete information disclosure for the pursuit of knowledge, and the supportive role played by informal and institutionalized norms that tend to reinforce cooperative behavior among scientists. It highlights the “incentive compatibility” of the key norm of disclosure within a collegiate reputation-based reward system that is grounded upon validated claims to priority in discovery or invention. In brief, rapid disclosure facilitates the rapid validation of findings, reduces excessive duplication of research effort, enlarges the domain of complementarities and creates beneficial “spill-overs” among research programs.[11]

Treating new findings as tantamount to being in the public domain fully exploits the “public goods” properties that permit knowledge and information to be concurrently shared in use and reused indefinitely, and thus promotes faster growth of the stock of knowledge. This contrasts with the information control and access restrictions that generally are required in order to appropriate private material benefits from the possession of (scientific and technological) knowledge. In the proprietary R&D regime, discoveries and inventions must either be held secret

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[11] It is the difficulty of monitoring research effort that make it necessary for both the open science system and the intellectual property regime to tie researchers’ rewards in one way or another to priority in the production of observable “research outputs” that can be submitted to “validity testing and valorization” whether directly by peer assessment, or indirectly through their application in the markets for goods and services.

or be "protected" by gaining monopoly rights to their commercial exploitation. Otherwise, the unlimited entry of competing users could destroy the private profitability of investing in research and development. One may then say, somewhat baldly, that the regime of proprietary technology (as a form of social organization) is conducive to the maximization of private wealth stocks that reflect current and expected future flows of economic rents (generating extra-normal profits). While the prospective award of exclusive "exploitation rights" has this effect (by strengthening incentives for private investments in R&D and innovative commercialization based on the new information), the restrictions that intellectual property monopolies impose on the use of that knowledge may perversely curtail the social benefits that it will yield. By contrast, because open science (again as a form of social organization) calls for the liberal dissemination of new information, it is more conducive to both the maximization of the rate of growth of society's stocks of reliable knowledge and to raising the marginal social rate of return from research expenditures. But it, too, is a somewhat flawed institutional mechanism: rivalries for priority in the revelation of discoveries and inventions may induce the withholding of information (i.e. "temporary suspension of cooperation") among close competitors in specific areas of ongoing research. Moreover, adherents to open science's disclosure norms cannot become economically self-sustaining: being obliged to quickly disclose what they learn and thereby to relinquish control over its economic exploitation, their research requires the support of charitable patrons or public funding agencies.

The two distinctive organizational regimes thus serve quite different purposes that are complementary and highly fruitful when they co-exist at the macro-institutional level. This functional juxtaposition suggests a logical explanation for their co-existence, and the perpetuation of institutional and cultural separations between the communities of researchers forming 'the Republic of Science' and those engaged in commercially-oriented R&D conducted under proprietary rules. Maintaining them in a productive balance, therefore, is the central task towards which informed science and technology policies must be directed. Yet, balancing the allocation of resources at the macro-institutional level and seeking to maintain both regimes within a single organization are quite different propositions. These alternative resource allocation mechanisms are not entirely compatible within a common institutional setting. *A fortiori,* within the same project organization there will be an unstable competitive tension between the two and the tendency is for the more fragile, cooperative micro-level arrangements and incentives to be undermined.[13]

2.3 STIG policies for complex systems: between coordination failures and "excess momentum"

While the inability of private agents to coordinate their investment plans in order to create mutual positive externalities, and thereby to increase both private and social returns from their respective innovations, has historically been recognized during periods of profound technological transition, a rather newer perception is that such inabilities reflect a generic source of "market failure" that calls for corrective policy responses. This perception is based on the recent view of the economy as an evolving complex system, characterized by positive feedback dynamics in some classes of markets, i.e., self-reinforcement mechanisms in which the management of innovational complementarities plays a major role in determining the motivation

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[13] Asymetries in the transition processes from openness to access restrictions and private property, on the one hand, and from private property to openness, on the other hand, have been analyzed by David and Foray (2001): in contrast to the former process, in the latter there is no spontaneous "phase transition". Thus, an individual (deviant) decision (towards openness and cooperation) is less likely to generating a movement towards a new equilibrium based on openness and cooperation than is the case in which the deviant decision of restricting access can cause a web of mutually supporting expectations of cooperative, open access to become unraveled. The threat of patent infringement suits is an especially potent one to deploy against rivals in lines of business characterised by high-fixed cost manufacturing operations: infringement suits, or even talk of being such actions, raises the spectre of court injunctions that can shut down production lines and thereby inflict substantial (non-) operating loses. The severity of the threat, however, can be mitigated if the targeted firm has undertaken prior investments in building up its' own patents, creating a base from which to file suits in retaliation. The role of this mechanism in driving a self-reinforcing cycle of patenting has been well analyzed and carefully documented by Hall and Ziedonis (2001), who found that in the US semi-conductor industry patent portfolios began to grow rapidly during the 1980s not as the result of increased investment in R&D to take advantage of new inventive opportunities, but as part of the firms' mutually reinforced perceptions of their vulnerabilities, and consequent need for self-protective strategies of patent trading and cross-licensing.

for, and the implementation of decentralized private investments in R&D. Positive feedbacks that arise from network externalities in the adoption of inter-operability standards in telecommunications and digital information processing systems can produce in two sharply contrasting forms of mal-allocation. The “chicken and egg” problem can result in the failure to attain the critical level of initial adoption of any standard that would drive its diffusion forward, so that the market would remain plagued by a diversity non-interoperable devices, and consequent losses the potential network benefits. On the other hand, it is now widely acknowledged that the dynamic instability created by positive network externalities may generate “bandwagon effects” in the adoption of a standard that attains critical mass at an early point in the network technology’s development. The “excess momentum” thereby created can drive the adoption process to a point at which the de facto industry standard that becomes entrenched cannot be dislodged by competition from a technically superior alternative, indeed, not even by one that majority of users would prefer were they able to exercise a choice outside the exiting context of the other standard’s dominant installed base of users[14].

It is attractive to think of using the structure of micro-level incentives created by complementarities in technical systems and organizational mechanisms to amplify the positive feedback effects of key policy interventions in order to propel the economy, or some large sectors thereof, to develop along a new techno-economic trajectory that would shift resources away from lower productivity uses and expand the future opportunity set of still higher productivity investments. This vision encourages the view that STIG policy should seek to identify and encourage certain classes of technology that provide “natural levers” to lift the economy’s rate of economic growth.

The concept of a “general purpose technology” (GPT) and its relationship to innovation, productivity improvement and the acceleration of economic growth offers an attractive rationale for government intervention (David, 1991; Bresnahan and Trajtenberg, 1995; Helpman, 1998; David and Wright, 2003). However, the aspect of GPTs that should render them most attractive for public policy planners is that they often give rise to noticeably “hot” areas of private technological research, where those engaged are enthusiastic about investing in commercialization opportunities that they believe soon to be within reach (biotech, nanotech,

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[14] See, e.g., David and Greenstein (1990) for a the review of the literature on the economics o f compatibility, or interoperability standardization as one industrial field illustrative of the two-sided problematic posed by positive market externalities.

synthetic biology, and so on). If the "GPT rationale" for focused programs of public investment is to be invoked persuasively, one should be able to make the case that the dynamics of development and diffusion of the new class of technologies is likely to be characterized by strong innovation complementarities between inventions and the "co-invention of applications". (Bresnahan, 2003).

In examining the mechanisms through which a GPT in the shape of information technology has contributed to late twentieth-century economic growth, Bresnahan (2003) stresses that the phenomenon of increasing returns of scale exhibits at the economy-wide level rests upon the complementarity of quite different forms of innovative activity. Positive feedbacks between the invention of new information technologies and the co-invention of applications in new domains take place concurrently in many particular markets; where there are innovative opportunities in two domains of invention, the process is one resembling "cross-catalysis", with positive feedback flowing back and forth and sustaining a temporally extended flow of advances. The development of very general scientific and technological knowledge, emerging from explorations of certain fundamental physical phenomena in a number of distinct domains where their potential applicability is recognized, in turn, forms a common foundation for specialized engineering advances in distinct industrial clusters. Opportunities are thereby created for further innovations that realize new technological functionalities from the design of products and systems than entail the *convergence* of previously distinct technological clusters, sometimes exploiting the complementarities between older and newer clusters. The convergence between the field of computing and the field of communication technologies that gave rise to the development of computer networks is a good case in point. Bioinformatics (or computational biology) which develops at the intersection of molecular biology and software methods is also a good example of technological convergence involving strong complementarities of quite different forms of innovative activity.

When things are going well in this way, one may stand back in awe at the unfolding of the process and its ability to sustain high marginal social and private rates of return on investment over an extended time-span. Yet, the complex relations between the invention and application sides in the development of economic activities in the GPT-nexus have, at their core, conditions that are potential sources of market failure. These are the concurrent and inter-temporal externalities created between invention and application that have been described by

Bresnahan (2003), but the experience gained in adoption may also provide informational externalities, which spill-over from pioneer users to hesitant adopters. Anticipation of opportunities to learn and profit from the experience of others can create incentives to delay adoption. The availability of a workforce with suitable technical skills is a condition on which information technology adoption decisions in business firms frequently depends, but is unlikely to materialize spontaneously until diffusion is quite far advanced. Moreover, the social benefits of rapid diffusion of a new technology may be postponed, in when network externalities are important might even be lost entirely if too many firms perceive that by delaying their investment in its acquisition, they can free-ride on the pioneer adopter's having built up workforce with the requisite technical skills that they could bid away without having to bear the , initial search and training costs.

Dynamic coordination failures are thus likely to arise from the very structure of complementarities in which the positive feedbacks associated with the GPT-based development are rooted. "Chicken and egg" situations do not automatically resolve themselves into action; excess inertia and the inability of the system to fully exploit the potentialities of the GPT are the "down" side of this bright coin. Appropriate policy responses in such complex settings are correspondingly more difficult to prescribe than those discussed in connection with cases involving essentially isolated "market failures" (see Section 2.1). They are closer in nature to the strategies for designing coordinated policies interventions in product and factor input markets that are closely coupled with scientific research and market-oriented R&D. The emphasis there fell upon the importance of devising an integrated set of mutually compatible and preferably mutually reinforcing policy actions ranging from government-sponsored research and public funding of basic research in university and government labs, R&D subsidies and tax credit incentives to more institutionally grounded policies that rendered labor markets more responsive and industrial relations more accommodating to the adjustments that the introduction of new innovations are likely to set in motion. But here, in addition, it is likely to be necessary for government policy to focus also on the demand side: public policy supporting innovation have proven to be especially effective where funding for R&D was combined with complementary policies supporting the adoption of innovation.

The policy design problem is challenging firstly because issues of timing are more delicate and the dynamic processes themselves are fraught with uncertainties: and secondly, because one cannot ignore the intricacies of constructing a technically interrelated system through the self-coordinated actions of decentralized innovators and producers of system components. As has been send, this challenge for policy-making is a particularly critical one where network externality effects are a key source of positive feedback. Special attention has to be given to the timely creation of conditions of interoperability, or technical compatibility, as these permit the realization of economic complementarities and of fruitful market and nonmarket interactions among organizationally and temporally distributed researchers, inventors, innovators, and end-users.

2.4 Institutions and human organizations: system structures or policy instruments (or both)?

As is true of institutions more generally, the specialize institutions and organizations engaged in the creation and transmission of technological knowledge are neither fixed nor exogenously determined. They emerge and evolve largely endogenously, shaped by the nature and the economic and social significance of the type of knowledge with which they are concerned, the interests they serve and the resources they are able to command through both market and political processes. But because institutional and organizational structures are less plastic and incrementally adaptable than technologies, they mobilize and deploy resources to stabilize those parts of their environment in which changes would otherwise be likely to undermine the economic rents being enjoyed by agents within them, although not necessarily by all the agents (see David 1994). Auto-protective responses of this kind may reinforce the stasis of other complementary elements of the institutional structure and so can work to impede beneficial innovation elsewhere in the system. Conglomeration is another strategy that may serve similarly defensive purposes: institutions sometimes find it attractive to take on new functions that actually do not have strong complementarities with the core functionalities and deeply embedded routines of the organization, yet provide additional access to resources, including coalitions of convenience with other entities.

Yet, being resistant to disruption of their learned internal routines, and on that account less plastic, formal institutions that seek to stabilize their external environments may become blind to the strength of the forces against which they are working. They are consequently vulnerable to drifting perilously close to the boundaries of their continued viability; becoming dysfunctional in devoting their resources to resisting forces that are driving transformations in the system around them, they may be subject to abrupt and catastrophic alteration: for example, being subjected to politically imposed “reforms”, captured and absorbed by other organizations, or dissolved and supplanted by newly created institutions. “Market failures” may be traced to obsolete institutions or perversely functioning procedures. Non-market institutions and organizations, i.e., those whose resource support is not drawn from their ability to sell goods and products to private parties in competitive markets in order to fund their own operations, nonetheless are not free from pressures that may transform and even extinguish them. Obviously, the same may be said for specific government organs and agencies.

The economic case for “reforms” of institutions that directly affect the performance of the STIG-system therefore separates into two branches: interventions to change institutions that are seen to be contributing to the inefficient outcome of market-directed processes; and reforms in the internal organizational structures and incentives of public institutions that perform badly in delivering services through non-market channels. Inasmuch as the research and training “products” of public-sector research organizations, including government institutes, universities, polytechnics and the like, are not priced and distributed through market channels, the criteria for determining where and when to make targeted interventions are vague. Being readily tied to the appropriation of public funding, the policy analysis is often framed in terms of tactical choices between decentralized guidance with well-defined incentives and performance targets, or centralized “command and control”. General theoretical insights from the economics literature on organizational design (e.g. Sah and Stiglitz, 1988) suggest that where the program requires high levels of specialized expertise, where information on which the resource allocation should be based is not symmetrically distributed, and where activity planning is highly contingent on the uncertain outcome of sequential production stages, decentralization of agenda control and flat organizations are preferable. This principle seems a reasonable rationale for large focused national programs that seek to mobilize the efforts of multiple public (and subsidized private) research and training organizations, including research universities, to create a knowledge infrastructure supporting innovation in a new research domain – nanotechnologies, for example. Yet, by the same token, it is vulnerable to substantial coordination problems and inertial drag in the responsiveness of the system to sudden shifts that may occur in the external scientific and intellectual environments, or in the conditions affecting governmental or private sector investment support.

There are many instances where a case can be made for internal institutional "reforms" because the performance of private R&D labs and public-sector research organizations is being adversely affected by the "rent-protecting" behavior of agents with vested interests. Another paper would be needed to fully develop and present the genesis and possible solution approaches to such situations, especially where the organization in question is buffered against the pressures of market competition or external "takeovers"; or where such extreme remedies are likely to disrupt functionally effective subunits that are "trapped" within a larger dysfunctional system. "Reforming" macro-institutional arrangements, such the legal regime of intellectual property rights, the legislative and administrative law frameworks that structure government university-industry R&D programs and projects, and the financing of research training in science and engineering, is an undertaking beset by formidable difficulties. These are structures (perhaps the term "systems" implies too much in the way of order and intentionality) that have evolved in an incremental, path-dependent fashion, responding at the margins to current pressures and opportunities to garner external support by taking on new missions for which they may not be particularly well suited. The modern patent and copyright systems offer a striking case of legal institutions whose role in the economy has evolved far from their initial historical purposes, and to which other organizations have become adapted even to the point of utilizing them for strategic ends quite inimical to the ostensible purposes on which their claim to legitimacy rests. (see for instance two recent books on this issue: Jaffe and Lerner, 2004, Bessen and Meurer, 2008).

"Institutional policy" is surely as important as other classes of government interventions that figured more prominently in the preceding discussion (of Sections 2.1 and 2.3), but institutions are neither technologies nor commodities. Although economists have much to contribute by analyzing the internal incentives and rule structures of specific existing organizations and institutions, and have developed techniques for evaluating alternative mechanism designs in similarly concrete situations, the present state of economic research on institutional dynamics offers few if any general, *a priori* points of guidance for policy reformers. Those who seek to stimulate innovation, say, by reforming intellectual property law, or the workings of patent offices, or the organization of research universities, are well advised to study closely the organizations' histories and professional cultures, as these shape individual behaviors and institutional performance, as well as the specifics of the material incentive structures that have evolved (endogenously) within them.

In this section we have revisited the literature on market failures. Starting from the Nelson/Arrow formulation of the *appropriability problem*, our exploration included the notions of *innovation complementarities and coordination failures* and of *endogenous evolution of institutions*. These are the three "themes" that have structured past and more recent research in the field of technology policy, while progressively broadening the dynamic system perspective. Each has generated the development of policy tools and instruments to which we now need to turn. .

3. Choosing "repair-tools"to fix "market failures": Neutral vs non-neutral instruments

Most of the market failures impeding investments in R&D are attractive targets for economic policy prescription because, more than others, they can be addressed with neutral instruments, i.e., without discrimination among technologies or sectors in the public funding allocation process, so that market signals remain the driving forces for the detailed allocation of investments by private agents and corporate bureaucracies. There is in this an explicit distrust of public agencies that are left to "pick winners" because bureaucrats are assumed to have no independent sources of expert knowledge and to give more weight to political considerations than to market signals. The empirical foundations for such sweeping judgments remain remarkably fragile[15].

Nevertheless, g*eneric* forms of subsidies (or tax credits) for the performance of R&D by private firms are held by many economists to be the most attractive public policy instrument to be employed to address the appropriability problem. These forms of support are favored because they are regarded as comparatively "neutral" with respect to the specifics of the research projects that are undertaken by the private sector. Neutrality means that funding organizations do not select projects according to preferred fields or any such criteria but respond to demand that arises spontaneously from industry. This greatly reduces the scope of government agency decision-making, and also the need for compliance monitoring of the performance of R&D projects.

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[15] Although the frequently asserted formula holds that *government*s cannot pick winners, *comparative* empirical evidence of the success-rates of public compared with private projects has not been adduced in support of the proposition, while exactly what is meant by being "a winner" is almost invariably left undefined.

Departing from neutrality with respect to technological fields is always dangerous since it implies guessing future technological and market developments.

Of course, an acknowledged and widely approved (or at least tolerated and institutionalized) policy departure from the neutrality principle is seen in the provision of differential support to the innovative activities of firms in different ranges of the size-distribution. The economic rationale for making such a distinction derives from the observation that large companies are usually considered in the literature as a relatively "efficient solution" to many of the problems raised by the allocation of resources to market-oriented R&D,[16] including those related to building relations with university research. Small firms, given their constrained resources, are likely to have greater difficulties in overcoming the various conditions that create the potential for market failure.

There is a logical problem here that is generally glossed over: if there are market failures, how can one assume private firms are getting the right signals from the market to make detailed decisions about technologies that will differ in factor input intensities, or among products serving different consumer needs and tastes? This is a replay of the now discredited 'neoclassical synthesis' of the 1950s and 1960s, which sought to reserve microeconomic resource allocation questions (and welfare analysis issues) for treatment with the conventional theories of the household and firm, embedded in competitive general equilibrium theory, while using Keynesian theory and policies to analyze and prescribe for better macroeconomic performance. The intellectual "patches" that for a while gave an appearance of holding those two quite disjoint theoretical frameworks together, became 'unglued' in the 1970s, creating the ongoing quest to provide more consistent micro-foundations for macroeconomics.

By contrast, STIG policies for complex systems activate a set of tools to target particular technological fields, to promote technological innovation in particular branches of industry, or to develop superior (e.g. "environmentally friendly") substitutes for specific resource inputs (such as oil or hardwood). These cannot help but depart from the principle of "neutrality" because specific technological and innovation projects will receive particular support. These policies

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[16] These problems include the inability to diversify risk where capital markets are incomplete or imperfect, the inability to minimize transaction costs when complete contracts cannot be written, the inability to capture spillovers or other externalities, etc. There is a strong presumption that vertical integration – by internalizing many externalities that would otherwise create difficulties in translating research into product innovation and production – provides the best solution for most of these economic problems. Schumpeter embraced essentially this view in *Capitalism, Socialism and Democracy*.

involve subsidy-programs for research, direct funding of research conducted by public research organizations (including tax-exempt educational and charitable institutions), and even contractual procurement of mission-oriented research in support of both civil government functions (e.g. public health services) and defense agencies. The reality is that such policies must be pushed in the face of concerted opposition from firms, or labor unions that view the intended technological advances as being in competition with their established lines of business or threatening to their employment security. Programs to promote the adoption of particular technological innovations, *a fortiori*, look like interventions that will create losers as well as winners; they invite stout opposition from the former, and so tend to be shunned as problematic, even if the overall net benefits for the private sector are perceived to be positive.[17]

Many controversial issues are at stake here. Obviously, government interventions that are explicitly differential in their intended impacts entail the risk of creating new market distortions, or of tilting rather than "leveling the playing field" for market competition. Thus, policymakers are generally cautioned by economists to avoid them, and to spurn the blandishments of those who lobby for a specific course of action with identifiable beneficiaries, except in cases where it can be said that there are glaring market failures that need to be remedied. There are at least three problems with this as practical policy advice. First, how "glaring" will any particular market need to be in the reality of a world that is riddled with market failures? If perfect competition under conditions of perfect information is the benchmark, determination of the extent of the inefficiency entails a counterfactual assessment that is hard to make, and harder still to make on a comparative basis. "Glaring", moreover, is a reaction that can be induced in the eyes of beholders by helping them to screen out signals of wasteful resource allocation elsewhere. Secondly, special interest groups are often the ones best positioned to gather the pertinent economic and technical information required to mount an argument that their chosen "market failure" should take priority over others in being remedied. Thirdly, when it comes to appropriations for subsidy and procurement programs, or the funding of specialized government research institutes and programs, budget constraints force priority-setting and choices that may be difficult to reverse significantly without writing off sunk costs and reducing the credibility of public policy commitment. Thus, the injunction to be "neutral", if it has any force at the margins

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[17] For this reason, while "innovation generating policies" (code for R&D-subsidy) may be quite popular, "diffusion" policies have long remained the "Cinderella of the Technology Policy Ball", waiting to capture the attention of some princely economist (see David 1986).

of decision-making, often operates to normalize and privilege the claims of established programs, which in many cases are the legacies of previous and glaringly non-neutral government policy commitments.

The argument “against” non-neutrality fails also to accurately recognize the historical evidence of many publicly subsidized science and technology programs that have yielded technical breakthroughs and a knowledge infrastructure that turned out to have significant commercial and productivity payoffs. Recent history of technology policy in OECD countries has shown that the creation of such strategic capabilities by non-neutral public research and training investments has repeatedly played an important role in building national leadership in “high tech” industries (see for instance the case of the U.S., National Research Council, 1999; Blumenthal, 1998; Mowery and Simcoe, 2002 but Japan, Korea, France or Singapour offer also examples of non-neutral policies aiming at building strategic capabilities in various fields). Furthermore, comparisons between good and bad historical experiences show that the very design of the policy as well as its harmony with competition policy (see next section) can have significant effects in mitigating some of the potential drawbacks of such non-neutral public programs.

In network industries, and in product markets characterized by network externality effects, a policy stance of avoiding deliberate standard-setting is not a strategy sufficient to prevent regrettable standardization outcomes, in which one becomes “locked in” to an inferior technical system that proves costly to abandon. Network externalities can also give rise to “excess momentum” in market-driven adoption bandwagons that will result in the premature extinction of a diversity of choice. This phenomenon is not without implications for technology policy. Perhaps the most productive question to ask is how we can identify situations in which, at some future time, most technology users would look back and agree that they would have been better off had they converged on the adoption of an alternative technical option (David, 1987). One thing that a managed government procurement policy could do in such circumstances is to intervene at an early stage to slow, or at least not to reinforce, the formation of premature “adoption bandwagons” among private-sector purchasers. Counteracting the development of irreversible interlocking investment commitments allows more time for new technological information and informed user data to emerge from a more symmetric competition among variant technological designs in the market, rather than leaving the advantage of network externalities with one design that happened to gain a relatively large installed base at an early stage in the process (see David, 1987, 2005).

In this section, we have discussed the economic nature of the policy instruments which are available to help correcting the various market failures identified above. Although neutral instruments usually are preferred as helpful and free of nasty side-effects (in that they do not create any further distortions in resource allocation), they are unlikely to increase the ability of an economy to shift research capabilities to more productive uses that is called for. Such policy goals imply a resort to non-neutral reallocations among specific technological or scientific research areas, and possibly among the economy's different sectors. But implementing non-neutral programs is always more hazardous politically, inasmuch it visibly favors some interests –seemingly at the expense of others, and it is predicated on taking a specific position as to where the best future technological and market opportunities are situated. developments. One is less likely to notice the opportunities that have been missed by pursuing a neutral policy strategy that increases aggregate R&D funding but spreading it out over so many fields and industries that economies of scale and critical mass fail to be achieved where they would do the greatest good. So a central practical problem is the design of programs that will be less exposed to the recognized potential sources of (risky bets on achieving uncertain technological break-throughs , picking winners in a political competition for funding support , "distorting" the future availability of products or proceses without having complete information about what future consumers would want). In a fundamental sense these hazards are inescapable. But non-neutral strategies that provide for on-going assessment and evaluation, and create options that preserve greater flexibility for mid-course corrections and even for radical program re-orientations, would appear to be the rational responses to this realistic policy challenge. .

4. Policy complementarities in a larger dynamic system perspective

The economic payoffs from public programs that aim to promote innovation by supporting private R&D investments are more likely to be disappointing, if indeed they materialize at all, when program design and implementation decisions fail to take account of the interdependence of the STIG subsystem with the economy as a whole. There is, therefore, a need to focus on the more "tightly coupled" elements and to give priority to identifying those that are strong complements of the activities or institutional structures that the policy intervention seeks to affect. This, in turn, calls for complementary policy interventions in order to promote positive feedback responses in the tightly-coupled parts of the economy, or at least to mitigate the force of negative feedbacks that can damp, or effectively counteract, the intended effects of the policy intervention targets to improve the performance in the STIG subsystem.

We therefore must take note of the need for some coordination across well-defended boundaries of specialization within the economic policy community. R&D subsidies strategies, for example, have been found to be rather ineffective when attention fails to be paid to the context set by policies for education and training, labour market policies, competition policy, and macro-economic stabilization policies (see Aghion and Howitt, 2005). In the following sections, these areas are examined briefly in turn.

4.1 Education

That education should be thought of as complementary to technical change and innovation was perhaps first pointed out by Nelson and Phelps (1966). According to them, a higher level of education should speed up the process of catching up with the technological frontier (or "best practice")[18]. There is in fact a fundamental complementarity between R&D investments and human capital in the process of building research capacity. Most R&D policies try to stimulate the demand for scientists and engineers in the private sectors through tax incentives and grants. To succeed, they depend on a positive supply response from the educational system. This is a crucial element: even a well-designed and generous program of R&D subsidies will fail to induce more innovation and faster growth if the education system does not provide sufficient supply of scientists and engineers. Endogenous growth theory shows that, in order to accelerate growth, it is not enough to increase R&D expenditures; rather it is necessary to increase the total quantity of inputs related to the R&D process (Romer, 2000).

4.2 Competition

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[18] The view that complementarities are reflected in differential "catch up" behavior has found support in tests based on cross-country panel data (see Krueger and Lindhal (2001). More recently, Aghion et al. (2005b), have decomposed education spending into "lower brow" and "higher brow" education, and shown that growth in countries or US states that are closer to the technological frontier (defined by relative productivity standings) benefits more from advanced (particularly graduate) education than does growth in those states further behind the frontier, whereas the latter enjoy greater positive effects on growth from increased investments at lower educational levels.

Easy entry into mature or new industries is a good thing; good by itself (since it means multiple and decentralized innovative experiments) and good in terms of stimulating the creativity of incumbents. R&D subsidies are therefore of little help if competitive pressures or the threat of entry do not keep firms on their toes and force them to innovate. Several empirical studies (e.g. by Nickell,1996) point to a positive effect of product market competition on patenting and productivity growth, especially at low levels of market competition, while Aghion and Howitt (2005) point to the positive effect of entry threats on incumbent firms' incentives to innovate. In the absence of true product market competition, R&D subsidies may end up being used by incumbent firms for other purposes, including creating barriers to entry,

4.3 Macroeconomics

One feature of private R&D investments is that they are very sensitive to economic cycles. Because such investments are uncertain and long term and involve sunk costs, firms operating in imperfect capital markets will tend to cut them when they experience a reduction in retained earnings or face an unexpected need to create reserves against major liabilities. In countries at a low level of financial development, the mechanisms and financial intermediaries to help firms overcome asset constraints while maintaining the research-based components of their innovation capabilities are often largely unavailable; and those that do exist will probably be overwhelmed if many firms experience correlated negative shocks from adverse macroeconomic developments. Proactive policies involving public spending, defence spending, direct subsidies to private R&D, and public procurement are therefore needed to maintain private innovative activities during the recession. In such circumstances, countercyclical budget deficits are not simply stabilizers but growth-promoting instruments (Aghion et al., 2005a). Countercyclical budgetary policy, however, is hard to implement, a practical consideration that will be considered in Section 5.

4.4 Labor market

When defined in the Schumpeterian sense of *creative destruction*, innovation requires labor market flexibility in order to minimize the cost of dismissing employees and to increase the ease with which the "destruction" of economically obsolete (or obsolescent) practices, forms and entire branches of industry can be realized. The costs of plant closures and worker layoffs are generally much higher in Europe (particularly continental Europe) than in the US. They are, in many ways, the most explicit manifestation of Europe's social welfare state and they are central to Europe's social model. In the absence of other changes, the US is therefore likely eventually to gain a competitive advantage in the introduction of innovative products and processes that entail job displacement, while Europe will become specialized in technology-following activities, based on secondary and less radical improvements. Viewed from this perspective, the gap between Europe and the US in terms of innovative capacity may be the price that Europe has to pay for not giving up its social model (see Soete, 2002).

In this section we have argued that a potential weakness of any private R&D investments support program is likely to materialize where complementary components (other important inputs, framework conditions) of the whole economic system are not adequately considered. Policy complementarities matter greatly, and R&D subsidies have been proven to be relatively ineffective when other basic innovation system ingredients are missing. Policy complementarities, however, raise difficult problems of coordination among different policy objectives, problems to which the discussion in the next section is addressed.

5. From theory to practice: how constrained is the actual scope for effective policy action?

The general concept of market failure is no longer such a controversial issue, while the various generic causes of market failures provide a theoretical framework to identify circumstances warranting the provision of public assistance to R&D and other innovation-related activities. Although in theory some forms of market failure are obvious, there is a second issue to be considered: *the practicality and cost of the policy intervention.* In certain situations even grossly inefficient market outcomes may turn out to be too expensive (or difficult) to correct.

5.1 The difficulties of practical implementation

A prime example of this is the case of sub-optimal coordination equilibrium, a product of the particular incremental evolution of complex technological systems. The end result, a system "locked in" to an inferior technology that is costly to scrap and replace (even if this was politically possible), may not be worth addressing if it has been allowed to become so deeply entrenched that other institutions and business practices, as well as technologies, have coalesced around it. Thinking about STIG policies in an historical framework leads one away from a static analysis of whether or not to intervene, on the evidence that there is market failure and a better arrangement is conceivable if one could start again with a clean state. Policy decisions will look differently when the options are evaluated at different points in time, that is to say, at different stages in the development of a new scientific field or in the diffusion of a novel technology. In general, thinking ahead and exercising some leverage on the process in its early stages entails smaller resource costs than those required for subsequent corrective actions. The only problem with acting on advice is that public agencies are likely to be at their most powerful in exercising influence upon the future trajectory of a network technology just when they know least about what should be done.

Another important practical challenge concerns the correction of coordination failures, which were identified above as an important potential obstacle to the full deployment of a GPT (Klette and Moen, 2000). Understanding the basic principles of coordination problems does not necessarily lead directly to useful conclusions about how to construct a suitable technology policy response. The practical implementation of a policy involves more than simply answering questions about what activities in what firms need to be coordinated and in what way. In particular, the appropriate choice of policy tools also requires a detailed technical grasp of the externalities and the innovative complementarities involved. Some economists have emphasized that the informational requirements at a practical level raise serious questions about the feasibility of government policy to correct coordination failures in the real world. For instance, Matsuyama (1997) argues that coordination problems are pervasive phenomena, and economists' articulation of coordination problems by means of simplistic game-theoretic models tends to trivialize the coordination difficulties that policy makers face in practice; in real coordination problems, the nature of the 'game', the payoff structure, the identity of the players and even their number may often be unknown to the policy maker.

Consequently, policymakers face immense difficulties in the practical implementation of a policy. Furthermore, we must bear in mind that firms may sometimes be able to implement cooperative solutions through negotiations and contractual relationships. The latter corresponds to the Coasean view of solving such coordination problems through market mechanisms. As a result, the significant costs of practical implementation and the possibility of firms themselves finding a solution through market mechanisms together point to a somewhat limited role for governments to overcome the coordination failures that diminish the returns on public and private investments in science, technology and innovation.

The US government's success in its role as coordinator in the case of IT is often taken as an example of what governments should do in other fields (National Research Council, 1999, Blumenthal, 1998, Mowery and Simcoe, 2002). However, that was a rather special case characterized by strong R&D investments in computer and computer networking technologies combined with a specific, high-priority government mission (national security). The US government has experienced difficulties in attempting to replicate that performance in other areas. Perhaps the repeated failures in energy technology R&D and diffusion policy (see, e.g. Jaffe et al. (2003)) are attributable to the absence of a strong link between R&D public spending and a government mission that can mobilize broad political support (Mowery, 2006).

The last example considered here involves the case of implementing a countercyclical policy to help financially constrained firms during recessions. Actually, countercyclical budgetary policy is harder to get right on purpose than by accident. Governments themselves must be able to access capital at an affordable cost in order to lend to the private sector in recessions. In addition, a countercyclical policy means that public deficits should be reduced once the recovery becomes firmly established. Possible solutions include the setting up of 'rainy day' funds with an independent authority determining whether the economy is in recession. Also, contingent public debt claims may help achieve a better countercyclical policy. Again, while the abstract concept of a policy defined as "helping firms to manage the cycle" is attractive, practical implementation seems hard to realize.

5.2 Enhancing the art of managing the complex system dynamics of innovation

The theory of technology policy may be reasonably good. Unfortunately, understanding the basic principles of market failures, coordination failures and policy complementarities does not take one very far in the direction of useful, practical conclusions about how to construct effective technology policy. There is a broad research agenda here to address such implementation issues.

"System dynamics" theory may offer a method for helping to understand the dynamic behavior of complex systems. The starting point is the recognition that the structure of any system, given the many circular, interlocking, sometimes time-delayed relationships among its components, is often just as important in determining its behavior as the individual components themselves. There are some features that are especially prominent in STIG and other tightly coupled subsystems of modern economies, particularly nonconvexities due to indivisibilities and externalities that create a multiplicity of ‘attractors’ or local equilibrium states (or paths in a dynamical system). In addition, the amplifying effects of positive feedback can produce strong nonlinearities in the response of agents, or whole subsystems, making it possible that the instabilities created by these feedbacks result in unexpectedly abrupt and discontinuous transitions, even formal mathematical “catastrophes”, between different states of the system. Therefore, one cannot rule out the possibility of surprising or even perverse outcomes emerging from what may appear to the unschooled policy-planner, at least, to be smooth, “incremental” adjustments in incentives or local targets, or a program of gradual modification of regulatory constraints intended to improve the performance of a particular market or institution.

However, recognizing that things may go badly awry, without at the same time being able to explore how sensitive the system is to modifications in one or several of its structures, may not be such a good thing as it sounds at first. The problem here is that a “little bit of knowledge” is likely to encourage policy inaction. Yet, as business decision-makers understand, or quickly come to learn, inaction is itself a strategy that can be punished severely by unfolding events driven by forces outside the decision-maker’s control. Suspending action in a battle requires suspending time, as Joshua’s command (“Sun stand Thou Still”) sought to do; but without being able to halt time and the actions of others can prove to be far more dangerous than experimenting with policies, especially if one acts in ways that are reversible or subject to subsequent corrective modifications. Consequently, we might conclude that an options-theoretic approach is called for: the expected costs of deferring investment to seize the gains from existing knowledge (in order to first collect more information) should continually be weighed against the expected costs of “prematurely” making commitments that subsequently turn out to be mistaken.

This sounds reassuring, but how can one assess those costs, and how can one identify those situations in which a policy commitment, once embarked upon, may become essentially impossible to reverse? The area of environmental policy is fraught with such traps: for example, lakes that become so polluted that they cannot clean themselves, and so on. The policy can be reversed, perhaps, but by then the action may well prove ineffectual, or will entail far greater resource costs than were sunk when it was first introduced. It was relatively costless to introduce structural reforms in the system of institutional patent agreements to automatically allow f US universities to obtain patents on the results of federally funded research, as was done in 1980 by the passage of the Bayh-Dole Act. A proposal today to modify the terms of the Act, let alone undo it, is likely to encounter fierce lobbying resistance not only from the administrators of universities that were lucky and smart enough to learn how to benefit from the new regime, but also from the new profession of university technology managers (who have their own professional association (AUTM), complete with a newsletter, offices in Washington, DC, and newly opened branches in Europe).

Clearly, some of these effects can be modeled in advance, and indeed simulation exercises could provide a framework in which to assemble and integrate empirical information about the behavior of various parts of the institutional, environmental, demographic, and governmental systems that interact. Moreover, development of the apparatus for such modeling exercises will surely force researchers to pay attention not only to how subsystems are linked with one another, but also to the vital question of the time lags and adjustment speeds that govern the propagation of responses through the system. This will doubtless expose some of the worst conceits and delusions of policy advocacy, in particular those regarding the question of how long it should take before the promised effects are realized. Unfortunately, this will not necessarily make it any easier to persuade government ministers and legislators to adopt sound STIG policies because most of the policy results will emerge too far in the future to be of immediate political interest. Nevertheless, at least it would contribute to clearing the air of some of the vague promises that this or that particular legal or institutional reform, administrative rule or tax measure affecting the funding of academic science or corporate R&D (or both) will combat unemployment, stimulate new firm growth, or reduce infant mortality in time for the next election campaign.

6. Concluding cautions about the ambitions of STIG policy research and practice

Technology and innovation policy for growth is widely accepted, but it immediately becomes politically controversial when its implementation goes beyond the support of "exploratory" and "far-from-commercialization" research, and enters into specific details that are perceived to have differential effects on particular markets, institutions and industries. There are good reasons for caution in entering those realms, but the growth potential of R&D and innovation is too clear to abandon policy efforts simply because they are difficult to implement or politically charged. It is therefore critical to experiment with different ways of structuring policy in this area so as to overcome the various conceptual and practical policy challenges. This essay has sought to confront these challenges by addressing the issue of the practical correction of market failures and policy coordination failures, by finding an appropriate systems paradigm and set of (simulation) tools to work within it in order to assess the dynamics of interactions among policy initiatives, and, finally, by addressing the problems of practical policy evaluation.

Closing words of caution are in order on at least two points, both having to do with "ambition". The first relates to the "scientific" ambitions of those who, through research, aim to improve the quality of STIG (and related) policy designs and their implementation. Complex systems give rise to "outcomes" that are driven by processes beyond the control of individual agencies or their policy advisors. One may experiment in a virtual environment using a simulation model to learn about certain qualitative dynamic properties of a complex system. However, simulation models often provide little information about critical determinants of the dynamics of systems of human actors, some of whom pursue adaptive strategies but not necessarily in all their spheres of activity. A further complicating factor is that policy-decision makers and implementation agents are themselves part of the interdependent processes and may contribute to the creation of destabilizing positive feedback dynamics. Empirical detail will best be absorbed into the structure of the model and the specification of its parameters only to specify some among the myriad features of the world that could be studied, and in order to quantify some dynamical relationships that are believed on analytical and experiential grounds to be critical in rendering the simulations able to provide robust insights that could be informative in setting policy strategies. The goal in such endeavors is, after all, not painstakingly realistic detail, but a simplified model or map with just enough detail to enable effective decisions to be made. The task of navigation in the terrain of "political economics" will not be advanced by furnishing either researchers or policy-makers with "a map that is as big as the territory".

Our last words are saved for those who aspire to "direct" the processes of scientific advance, technological change, and innovation along certain trajectories so as to improve the economic welfare and material well-being of societies and nations. Public agency interventions in STIG processes are unlikely to yield political credits in the time frame within which most politicians and public servants in representative democracies have to function, unless their objectives are confined to redistributing resources gathered by taxation among their respective constituents. In the realms where creating new scientific and technological knowledge and finding the most effective ways to use it are central, the advances are mostly incremental and cumulative over long periods. Hence, the assignment of responsibilities for significant successes can only be retrospective rather than contemporaneous. Moreover, in complex, contingent, and at best only partially understood dynamical processes, individuals who seek to claim responsibility for changing the system's "performance" for the better are all too likely to find that they are the recipients of blame (albeit in many instances equally unjustified) for outcomes that were unanticipated and unwanted.

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