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Linking Policy Research and Practice in 'STIG Systems': Many Obstacles, but Some Ways Forward

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Abstract

This paper reflects on the relevance of "systems-theoretic" approaches to the interdependent policy issues bearing on the dynamics of science, technology and innovation in 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 while also acknowledging their more serious problematic features. The latter become visible quickly when one tries to connect systems-relevant research with practical policy-making in this field. Not content to have simply identified a number of the significant obstructions encountered in the path toward that goal, the paper also suggests some potentially feasible ways forward.

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1. INTRODUCTION

Studies of the political economy of science and technology policy, and of the sociology of scientific knowledge and the "social shaping of technology" have proliferated noticeably in recent years, raising critical questions about the social desirability of the directions in which scientific and technological research and development are channeled in modern societies. Economic research addressing science and technology policy matters, however, has remained preoccupied with something else. Interest in R&D and innovation policy has perked up recently in academic economics, even among researchers disposed to follow the discipline's "mainstream". Undoubtedly, this development reflects the widely shared perception that the differentially higher levels and rates of growth of measured total factor productivity enjoyed by some national economies are attributable to the greater success sustained by those countries in exploiting emerging technological opportunities. Most of the economists drawn to this area are intrigued by the possibility that the good results observed can be traced to good 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.

For the most part, the contributions of economic research 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 a stock of generic knowledge; the latter, conveniently, is 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[1]. 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 avoiding having to take notice of 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 very heterogeneous informational novelties with increases in the measured (or notionally measurable) 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, without allowing it to be immediately emmeshed in choices among concrete societal options, and, instead to consider the most generic class of policy problem. This is the issue of whether the right amount of investment is being allocated to the production and dissemination of new research results, which

[1] We take care to distinguish "information" (which here is conceptualized as "structured data") from "knowledge"(viewed as a particular class of human cognitive capabilities). The latter can be used to gather and filter data, extract information from it, and translate information-signals into a variety of actions. This relational schema and its connections with codification are further elaborated by Cowan, David and Foray (2000); David and Foray (2001).

translates into the question of whether the institutionalized and informal processes of information 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.

The foregoing quite clearly is something of an over-simplification, which is meant to capture key features of the underlying conceptual framework that orders the prevailing economic approach to myriad issues that engage the attentions of specialist researchers in the science, technology and innovation policy. Rather than being treated in isolation as distinct and separate topics,[2] they 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 open 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 them in selecting and designing programs to affect the production, distribution and utilization of scientific and technical data and information? Some researchers have expressed serious intellectual grounds for 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 interventions in the workings of markets.

For government to undertake 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 would be case with 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?

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 hand, encourages the conceptualization of "science, technology, innovation and growth systems" (STIGS) as appropriate subjects for policy-oriented research. Alternative conceptual frameworks, including those more accommodating to evolutionary

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[2] 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 "sub-fields" can be found in the *Journal of Economic Literature's widely used* classification scheme. That omission poses an interesting anomaly for study by 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 among those departments.

analysis of the dynamics of complex systems, may readily spring to mind here. Certainly they 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 poorly performing markets. The important question that then presents itself is whether, within such a paradigm, it really will be feasible to design and evaluate appropriate policy interventions. This paper revisits a number of favorite topics in that spirit and discusses some implications of taking a larger system perspective for policy analysis.

Our discussion of these fraught questions follows a line of argument that is set out in the next six sections. Section 2 presents an overview of STIG policy that integrates the market failure rationale for policy with a broader system perspective. The market failure rationale for technology policy rooted in Nelson (1959) and Arrow (1962) has been more recently further elabourated by consideration of the implications of innovation complementarities, coordination and system failures, and the economics of 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 argument that a "correct" policy needs to be neutral and non-specific with respect to technologies and firms, and to assess the extent to which the STIG perspective provides some economic rationale for non-neutral polity interventions. That perspective is widened,in Section 4, which explicitly recognizes critical aspects of interdependence between STIG-policy and the pursuit of related or independent goals by other classes of economic policy – those conceived of as having primary impacts on human capital formation, macroeconomic performance, effective competition, the efficiency and flexibility of labour markets, and the stability and responsiveness of financial institutions. A potential weakness of any technology policy is likely to materialize where the complementary components of the whole economic system are not 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 the direction of deriving practical recommendations about the construction of effective policy "interventions" (or decisions to defer intervention) that must be executed in real time. The practical difficulties of designing "interventions" for a system of such complexity pose formidable challenges, because it must be recognized that at least some among the conditions that call for government policy interventions also imply that important aspects of the system's behaviour may be "emergent properties" that cannot reliably be deduced from a knowledge of the properties of its constituent parts. An attractive path of escape from this conundrum is indicated in the last part of this section, where it is suggested that greater recourse should be made to the approach and tools that are being developed and deployed in the field of *system dynamics* **--** particularly the methods of "virtual experimentation" using stochastic simulation models.

Evaluation issues are addressed in Section 6: the problems of estimating counterfactual outcomes to demonstrate the effectiveness of a particular policy action, especially in situations where general equilibrium effects may be involved, are discussed, along with the proposed use of randomized trials to produce empirical proof of causal effects. General equilibrium effects re-enter consideration of the question of how to "scale up" from results of small scale, localized experimental trials. The use of simulation in this systems context is seen to provide a means of integrating and appropriately "scaling up" particular empirical findings obtained (as is now widely advocated) from controlled and therefore necessarily partial studies designed to statistically identify the differential effects of alternative program structures and policy instruments.

The paper concludes with a few cautionary reminders of the political hazards that await policy researchers and practitioners who succumb to the hubris of suggesting 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 sub-optimal. 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 to generate "intertemporal knowledge spillovers" (see, e.g., Dasgupta and David (1994), Aghion and Howitt (1998)). This characteristic is a form of non-convexity, or an extreme form of decreasing marginal costs as the scale of use is increased: although the cost of the first instance of use of new information may be large, in that it includes the cost of its generation, further instances of its use impose at most 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 data and information, like the acquisition of access are processes that entail fixed costs, the existence of the latter does not vitiate the proposition that re-use of the information will neither deplete it nor impose significant further (marginal) costs. A second peculiar property of ideas that should be underscored here is the difficultly 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 idea, the production of visible results that were not otherwise achievable will disclose (at very least) that a method exists for obtaining that effect. Quite understandably, scientific and technical results obtained by methods that cannot or will not be disclosed are felt to be less dependable on that account; their production is deemed to be more in the nature of magical performances than as contributions that would enlarge the corpus of reliable knowledge.3

The dual properties of non-rival usage and costly exclusion of others from possession define what economists mean when they speak of "pure 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 pure public goods is the proposition that competitive market processes will not do an efficient 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 of commodity’s general nature and significance (let alone its exact specifications) to a purchaser consummating a market transaction can yield valuable "transactional spill-overs" to potential purchasers, who would remain 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 those 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 whose specifications 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 “appropriablity problem,” the existence of which is invoked in the mainstream economics literature as the primary rationale for the government interventions by means of various public policy instruments. The recommended policy response to the diagnosis of a chronic condition of under-investment in scientific and technological research by the private sector is that the public sector should first do things to increase R&D expenditures, using general tax revenues for the purpose. A number of principles are advanced as guidance for such interventions, some which turn out to be less compelling than would appear at first sight.

[3] Even the offer of a general explanation of the basis for achieving a particular, observable result may be sufficient to jeopardize the exclusivity of its possession, because the knowledge that something can be done is itself an important step toward discovering how it may be done. Thus, resources are devoted to “reverse engineering” new artifacts with a view to devising still other ways of producing them, or other artifacts sharing their valued properties.

2.2 "Open science" and proprietary research—wonderful but flawed organisational regimes

Part of the conventional market failure justification offered for government intervention in the sphere of scientific and technological research and development recognized a difference between exploratory or "fundamental" or "basic research", on one side, and "applied" or "commercially-oriented" R&D, on the other. The special need to subsidize the former has been found in its greater uncertainties, 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 organisational and incentive mechanisms that government support maintains, and works through in order to provide economic support for research activities. More recent institutional analysis associated with the so-called "new economics of science"has offers 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.

The modern rationale for public policies supporting "open science" focuses on the economic and social efficiency properties 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 behaviours among scientists (Dasgupta and David 1994). 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 disclosures abet rapid validation of findings, reduce excess duplication of research effort, enlarge the domain of complementarities and yield beneficial "spill-overs" among research programs.[4]

Treating new findings as tantamount to being in the public domain fully exploits the "public goods" properties that permit data and information to be concurrently shared in use and re-used 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 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 (*qua* social organisation) is conducive to the maximization of private wealth stocks that reflect current and expected future flows of economic rents (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 IP monopolies impose on the use of that knowledge perversely curtail the social benefits that it will yield. By contrast, because open science (*qua* social organisation) calls for 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 flawed institutional

[4] Without delving deeper into the details of this analysis, it may be noted that 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.

mechanism: rivalries for priority in the revelation of discoveries and inventions induce the withholding of information ("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 organisational 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 who are 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 organisationorganisation are quite different propositions. These alternative resource allocation mechanisms are not entirely compatible within a common institutional setting; *a fortiori,* within same project organisation 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.

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 (such dawning of the canal era and the railways), rather newer perception is that such inabilities reflects 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, exhibiting properties of increasing returns and self-reinforcing mechanisms in which the management of innovational complementarities play a major role in determining the motivation for and the performance of decentralized private investments in R&D. In this case, the move towards a new technological system only can take place when the country in question exhibits effective strategic capacities, that is the capacity of governments to create satisfactory incentives and motivations to move the whole system toward the new technology.

It is attractive to think of using the structure of micro-level incentives created by complementarities in technical systems and organisational mechanisms to amplify the 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 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. Accompanying that notion, however, should come an appreciation that such "levers as may present themselves are likely to be few and far between during any reasonable policy-planning time-span, and that the unfolding process of exploiting their potentialities to accelerate economic growth will extend over a considerably period. Furthermore, it is also likely that their emergence will be equally apparent to policy-planner in other economies. Success, and especially comparative success in pursuing such a strategy, therefore, is likely to turn on something else than mere identification of the existence of the potentialities created by a change in the technologic opportunity set. That "something else" is precisely the capability of those responsible for managing this kind of public policy intervention to anticipate, and to avert coordination failures that otherwise would prevent the formation of positive-feedback dynamics in a "virtuous spiral," rather than the opposite.

The recent popularity of the concept of a "general purpose technology" (GPT) and its relationship to innovation, productivity improvement and acceleration of economic growth offers an attractive case for government intervention (David, 1991;Bresnahan and Trajtenberg, 1995; Helpman, 1998; David and Wright, 2003). But the aspect of GPTs that should render them attractive for public policy planners is not 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 be within reach (biotech, nanotech, synthetic biology, and so on). If the "the GPT rationale" for focused programs of public investment is to be invoked persuasive, 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."

The GPT-inventions' success involves two mechanisms that are coupled, so that the economy's "invention possibility frontier" is shifted outward by the complementarities of fundamental scientific and engineering advances with concurrent applications innovations in many potentially inter-related domains. Co-invention shifts the production possibility frontiers of a particular groups of activities outwards, lowering real costs and improving performance that expands the markets for information technology applications, and raises the prospective payoffs to further inventive and innovative investments. In examining the mechanism's 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 socially increasing returns of scale that is manifested 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 co-invention of applications in new domains appear 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 functionalities and technological affordances 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 of digital computing and telecommunication, and the applications of both in the production of digital on-line text, images and sound, are by now familiar examples of the power of these process to not only create new goods and services, but also altered the boundaries of business enterprise, change the nature of market competition, and disrupt the structure of industries.

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 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, and the non-convexities created by the technical interrelatedness of investments, which can set the stage for the failures in investment coordination that are likely when enterprises in new field find it difficult to gain access to continuing lines of financing, and cannot acquire control of assets that would allow them to internalize the key dynamic externalities. Early users' experience is an externality, spilling out from pioneer users to hesitant adopters, and the opportunity to learn from the experience of others creates an incentive to delay adoption; the availability of a workforce with suitable technical skills is a condition on which ICT adoption decisions in business firms frequency depends, but is unlikely to materialize spontaneously until diffusion is quite far advanced.

Dynamic coordination failures are thus likely to arise from the very structure of complementarities in which the social increasing returns 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" (in 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 mutual 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 labour markets more responsive and industrial relations more accommodating of 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 interventions to be coordinated not only on the supply side, but also to align the development of demands for complementary innovations with the development of supply capacities that will allow them to come to the market concurrently, so that their diffusion into use can be mutually reinforcing.[5]

2.4 Coordination failures and standardization policy

The policy design problem is more challenging both because issues of timing are more delicate and the dynamic processes themselves are fraught with uncertainties: also, 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. This challenge for policy-making is a particularly critical one where network externality effects are a dominant source of positive feedbacks. Special attention has to be given to the timely creation of conditions of interoperability or technical

[5] This was Ragnar Nurske's contribution to the "big push" strategy of development, which, in the 1950's and early 1960's was a popular rationale for development policies featuring complementary import-substitution investment.

compatibility, as these permit the realization of economic complementaries and fruitful market and non-market interactions among organisationally and temporally distributed researchers, inventors, innovators, and end-users. Anticipatory standard-setting is recognized to have the power to define markets and structure competition in the markets for newly emerging ICT goods and services, enabling some producers to look forward to attaining efficient scales of production and the learning experience acquired in the process (see, e.g., David and Steinmueller (1994)). Standards also can exert important effects on the nature and direction of research and inventive activity. The existence of *de facto* industry standards, and of specifications set *de jure* by regulatory authorities, tends to focus the attention of competing producers on specialization in incremental elaborations of one or another of the components – contributing to improving the performance and commercial success of the emerging technological system. There is thus a difficult trade-off problem here: delivering the benefits of deployment and diffusion by encouraging standard-setting tends to truncate the process of exploring the technological opportunity space, which is more likely to continue with vigor when rival firms are contending to pour resources into R&D, seeking discrete ("drastic") new product designs in a Schumpeterian competition for the whole market.

Approaching this policy choice with the principle of "the golden mean" in mind encourages one to seek a point of balance between sacrificing the benefits of improved future returns on innovation investment by setting standards, and deferring realization of benefits from deploying an available and incrementally improvable system--in the hope of learning whether a much superior version might be attainable. This is the familiar search in welfare analysis for an "an interior optimum" that represents a compromise, or best trade-off between the alternatives offered by the two "pure" strategies: push standards or don't push standards. But, the supposition that such an optimum is to be found may not be justified: as David and Rothwell (1996) show, there are some realistic industrial conditions (arising from non-convexities) under which either of the pure strategies in regard to standardization turns out to dominate the intermediate, or "mixed strategy", solutions to the policy optimization problem.

This, however, should not be interpreted as saying that standardization policy for technological fields and the industries based upon them should be formulated in stationary, once-and-for all terms. Quite the contrary, the dynamics of industrial development around emerging technologies calls for a corresponding non-stationary approach to standard-setting. Anticipatory, meta-standards that accommodate exploration of a wider and more radically varying range of engineering designs generally are more appropriate for the earlier stages in the emergence of a new network technology, but, eventually these should be supplanted by a restricted range of specifications that support widening technical compatibility and interoperability of system components, and thereby broaden the applicability of subsequent incremental innovations.[6]

[6] See e.g. David (1987, 1995). Managing dynamic systems in which there are competing technological options that are subject to endogenous improvements through positive feedbacks from government procurement decisions poses challenging control problems under deterministic conditions. Under uncertainty, mistakes are almost bound to occur -- leading to commitments to standardize on systems whose performance could have been dominated by the selection of a different variant on which to set procurement standards. This is an instantiation of the more general stochastic "lock-in" problem analysed by Cowan (1991), and which recurs in the literature on path dependence in technological systems (see David 2005, 2007).

2.5 Institutions and human organisations: system structures or policy instruments, or both?

Institutions and organisations engaged in the creation and transmission of technological knowledge, like institutions for other purposes, are neither fixed nor exogenously determined. They emerge and evolve 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 organisational structure 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 organisation, 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, it also the case that formal institutions that seek to stabilize their external environments also 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 system around them, they are subject to abrupt and catastrophic alteration: subjected to politically imposed "reforms", captured and absorbed by other organisation, or dissolved and supplanted by newly created institutions). "Market failures" may be traced to obsolete institutions or perversely functioning procedures. Non-market institutions and organisations, i.e., those whose resource support is not drawn from their ability to sell goods and products to private parties on 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 organisational 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 organisations, 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, and tend to be arrived at *ad hoc*. Being readily tied to the appropriation of public funding, the policy analysis thens to be 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 organisational design (see e.g., Sah and Stiglitz (1988)) suggest that where the program involves high inputs of specialized expertise, where information on which 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 organisations 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 organisations, including research universities, to create a knowledge infrastructure supporting innovation in a new research doman – nanotechnologies, for example.. But, by the same token, it invites substantial coordination problems and inertial drag in the responsiveness of the system to sudden shifts that may occurs in the external scientific and intellectual environments, or in the conditions affecting governmental or private sector investment support.

There are many instance 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" behaviours 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 organisation in question are buffered against the pressures of market competition or external "take-overs"; or where such extreme remedies are likely to disrupt functionally effective sub-units 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 research training in science and engineering, is generally an undertaking beset by formidable difficulties. These are structures (perhaps "systems" implies too much in the way of order and intentionality) that have evolved in increment, 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 other organisations 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: think of the U.S.constitutional foundations for the grant of copyright and patent privileges to promote invention and further cultural and scholarly production, and the growing trend toward the use of those (intellectual) property rights by business firms to raise rivals costs, deter entry into their markets, block the commercialization of inventions and discoveries. The one thing on which most economic and legal experts in these matters seem able to agree is that these institutions would look very different were it possible now to re-design them *de novo*, and yet the best that can be hoped for is to remedy the most perverse aspects of their workings (see e.g.,David, 1993, 2006).

"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, and although economists have much to contribute by analyzing the internal incentives and rule structures of specific existing organisations 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 organisation of research universities, are well advised to study closely the oganisations' histories and professional cultures, as these shape individual behaviours and institutional performance, as well as the specifics of the material incentive structures that have evolved (endogenously) within them. In other words, development policy experienced, which involves some immersion in the local culture and a grasp of the inherited constraints on the melioration of dysfunctional performance (without disrupting the routines that permit continuing fulfillment of vital functions upon which external agents and agencies relay) seem a no less promising practical route to success in addressing needs for institutional reform in developed economies.

3. INSIDE THE “REPAIR-TOOL BOX” : NEUTRAL AND 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 it is claimed that qua bureaucrats the personnel have no independence sources of expert knowledge, and they are likely to be predisposed to attend to political considerations more closely than to market signals. The empirical foundations for such sweeping judgements remain remarkably fragile[7].

Nevertheless, g*eneric* forms of subsidies (or tax credits) for performance of R&D by private firms are held by many economists to be the most self-evidently 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” or “blind” with respect to the specifics of the research projects that are undertaken by the private sector. This greatly reduces government agency decision-making, and the need for compliance monitoring of the performance of R&D projects. Economists’ recommendations for non-specific forms of subsidization in this area find political backers the more readily because it is easier to build a large supporting coalition if the policy prescription does not narrow the list of potential subsidy receivers. They have a focused common interest, and the costs of the subsidy will be spread widely among the tax-paying public – perhaps too widely to be noticed.

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 “an efficient solution” to many of the problems raised by the allocation of resources to market-oriented R&D,[8] including those related to building relations with university research. SMEs, given their constrained resources, are likely to have comparatively greater difficulties in overcoming the various conditions that have been noted as creating potentials for market failure.

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7 Although the frequently asserted formula holds is that *government*s cannot pick winners, but *comparative* empirical evidence of public-vs private project success-rates has not been adduced in support of the proposition’s validity, and what is meant by being “a winner” is almost invariably left undefined.

8 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 a first-best solution for most of these economic problems. Schumpeter embraced essentially this view in *Capitalism, Socialism and Democracy*.

There is a logical problem here that is generally glossed over: if there are market failures, how can it be supposed that 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 1960's, which sought to reseserve 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 analyse 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 1970's, creating the ongoing quest to provide satisfactorily consistent micro-foundations for macroeconomics.

By contrast, STIG policies for complex systema, activate a set of tools to target some particular technological fields, promote technological innovation in particular branches of industry, or develop superior (e.g., "environmentally friendly") substitutes for specific resource inputs (such as oil, or hardwoods). These cannot help but depart from "neutrality" because specific technological and innovation projects will receive particular supports. These policies involve subsidy-programs for research, direct funding of research conducted by public research organisations (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 labour unions that view the intended technological advances as competitive with their established lines of business or threatening to their employment security. Programs that would promote the adoption of particular technological innovations, *a fortiori*, look like interventions that would 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.[9]

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 tilting rather than "leveling the playing-field" for market competition. Thus, policymakers are generally cautioned by economists to avoid it, 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 appear 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

[9] For this reason, by comparison with the popularity of "innovation generating policies" (code for R&D-subsidy), "diffusion" policies have long remained the "Cinderella of the Technology Policy Ball" – waiting to capture the attentions of some princely economist (see David 1986)..

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 of decision-making, operates to normalize and privilege the claims of established programs – which in many cases are the legacies of previous, 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 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 have shown that the creation of such strategic capabilities by non-neutral public research and training investments has repeated played an important role in building of the US leadership in "high tech" industries (National Research Council, 1999, Blumenthal, 1998, Mowery and Simcoe, 2002). Furthermore, comparisons between some 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 – those seen to have "locked in" an inferior technical system that will prove costly to abandon. Network externalities give rise to "excess momentum" in market driven adoption bandwagons. This phenomenon is not without implications for technology policy: David (1987,) suggests that perhaps the most productive question to ask is how can we identify and focus upon situations in which it is highly likely that at some future point in time most technology users would look back and agree that they would currently be better off had they converged on the adoption of one of the alternative technical options that was then available. One thing that a managed government procurement policy could do in such circumstances is to intervene at an early stage, when exploration of the technology opportunities that have greater potential to reveal promising options, to slow or at least not reinforce the formation of pre-mature "adoption bandwagons," among private sector purchasers. Counter-acting the development of irreversible inter-locking investment commitments works to allow 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 point in the process (see David, 2005).

4. POLICY COMPLEMENTARITIES IN A LARGER DYNAMIC SYSTEM PERSPECTIVES

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 decision fail to take account of the interdependence of the STIG sub-system with the economy as a whole. There is, thus, a need to focus on the more "tightly coupled" elements and give priority to identifying the ones that are strong complements of the activities or institutional structures that the policy intervention seeks to affect. Complements call 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 sub-system.

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

4.1 Education

That education should be thought of as complementary to technical change and innovation, was 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")[10]. 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

Easy entry is a good thing; good by itself (since it means multiple and decentralized innovative experiments) and good in stimulating the creativity of incumbents. R&D subsidies therefore are of little help if competitive pressures or the threat of entry do not keep firms on their toes and force them to innovate. Recent empirical studies (e.g by Nickell (1996), Blundell et al (1995), and Aghion et al (2005b)) point to a positive effect of product market competition on patenting and productivity growth, especially at low levels of market competition: and Aghion et al (2006) point to the positive effect of entry threats on incumbent firms' incentives to innovate. In the absence of true product

[10] The view that complementarities are reflected in differential "catch up" behaviour has found support in tests based on cross-country panel data (see Benhabib and Spiegel (1994), and Krueger and Lindhal (2001). More recently, Vandenbusshe et al. (2004) and Aghion et al. (2005c), have decomposed education spending or attainment 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 do those further below the frontier; whereas the latter enjoy greater positive effects on growth from increased investments at the lower educational levels. Observations from the long-run historical experience of the US and other industrial economies are quite consistent with these econometric findings: see David and Goddard (2003) for a review of empirical research on issues of convergence, catch up and human capital formation.

market competition, R&D subsidies may end up being used by incumbent firms for other purposes -- including as barriers to entry,.

4.3 Macroeconomics

One feature of private R&D investments is that they are very sensitive to economic cycles. They are uncertain and long term, and they involve sunk costs. In the context of imperfect capital markets, it is therefore obvious that firms will cut them when they encounter a shrinkage in retained earnings or have unexpected needs to devote free cashflow to creating reserves against major liabilities. When countries have a low degree of financial development, the mechanisms and financial intermediaries that can help firms to overcome asset constraints while maintaining the research-based components of their innovation capabilities are likely to be largely unavailable; those that exist will be over-whelmed if many firms experience correlated negative shocks from adverse macroeconomic development. Proactive policies – involving public spending, defence spending, direct subsidies to private R&D, public procurement – therefore would be needed to maintain private innovative activities during the recession period. In such circumstances, countercyclical budget deficits become not simply stabilisers, but growth-promoting instruments. The case of Europe illustrates the lack of policy at this level: the stability pact overvalues stability against growth; it defines a procedure of mutual control of public deficit of the member states and militates against a framework in which budgetary policies could be developed as countercyclical mechanisms. The US case shows just the opposite, even though the country is more financially developed than the EU. A recent study by Aghion et al. (2005a) suggests that annual growth rate in the EMU area could increase by up to 0.7% if public debt growth became as countercyclical as in the US. Countercyclical budgetary policy, however, is hard to implement, a practical consideration of the kind that will be considered in Section 5.

4.4 Labour market

When defined in the Schumpeterian sense as *creative destruction*, innovation requires labour market flexibility in order to minimize the cost of dismissing employees and increase the ease with which the "destruction" of economically obsolete and obsolescent practices, forms and entire branches of industryi can be realized (Saint Paul, 2002). These costs of plant closings 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 therefore is likely eventually to gain a competitive advantage in the introduction of new, innovative products and processes that entail job displacement, while Europe will become specialized in technology-following activities, based on secondary, less radical improvements. Viewed from this perspective, the gap between Europe and the US in terms of innovative capacity may also be the price Europe has to pay for not wanting to give up its social model. In this respect the Lisbon strategy of seeking a substantial region-wide increase in the rate of investment in R&D may be seen to reflect a fundamental tension between the goal of gaining international competitiveness as route to employment creation, and the objective of maintaining the social model (see Soete, 2002).

One may note, finally, that any evolution in the direction of higher labour market flexibility and lower costs of job displacement due to innovative activity needs to be supported by the development of *life-long learning capacities*. "Creative destruction" of occupations and particular skills is socially more acceptable and economically less wastefull if individuals have acquired the capabilities to confront constant changes and transfer their skills-learning capacity from old to new settings. Reconciling the need for flexibility on the side of firms, with the enhancement of employees' incentives and ability to invest in skill acquisition so as to move easily from one job to another, is likely to require active labour market policies of the type pioneered in Denmark. These, in turn, are quite costly, which adds to the importance of adequate macroeconomic management as a strong-augmenting tool.

For all of these issues, it would be a major mistake to concentrate on a single policy measure while ignoring others that could be inconsistent with attaining the objections that particular science and technology policies are intended to secure. Policy complementarities, however, raise difficult problem of coordination among different policy objectives, a problem to which the discussion in the next section is addressed.

5. FROM THEORY TO PRACTICE : TOWARD A MORE LIMITED ROLE FOR GOVERNMENTS?

The general concept of market failure is no longer a controversial issue and 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. While in theory some cases of market failures are obvious, there is a second issue to be considered: *the practicality and cost of the policy intervention.* Certain types of market failures may be too expensive (or difficult) to correct.

5.1 The difficulties of practical implementation

A prime example of this is the case of bad coordination equilibrium, a result of some particular properties of the sequential and incremental evolution of complex technological systems. The end result – a system that has "locked in" to an inferior technology that is costly to simply scrap and replace, even if this was politically possible – may not be worth undoing if it has been allowed to be deeply entrenched so that other institutions and business practices, as well as technologies, have formed around it. The lesson of thinking about STIG policies in an historical framework is that one is led 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 and with a clear slate. Policy decisions will look differently when the options are evaluated at different points in time, that is to say, at different moments 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 will be required for corrective actions subsequently. The only problem with acting on advice is the comparative dearth of information about what one should do at the moments when policy actions would have greatest potency.

Another important practical challenge concerns the correction of coordination failures, 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 lead directly to useful, conclusions about how to construct a suitable technology policy response. The practical implementation of a policy involves answering more than a simple set of questions: what activities in what firms need to be coordinated, and in what way? 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 raises 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 face policy makers. In real coordination problems, the nature of the 'game', the pay-off structure, the identity of the players and even their number are often unknown to the policy maker.

Thus, policymakers face immense difficulties in the course of the practical implementation of a policy. Moreover, it is not obvious that firms will always be unable to implement cooperative solutions through negotiations and contractual relationships. The latter is the Coasean view of solving such coordination problems through market mechanisms. As a result, the appreciation of the costs of practical implementation and the appreciation of a possibility of a solution provided through market mechanisms point to a similar conclusion about the limited role for governments to act effectively to overcome coordination failures that diminish the returns on public and private investments in science, technology and innovation.

The US government role as a successful coordinator in the case of IT often is taken as an example of what government should do in other field. That case, however, involved a very particular context characterized by a strong identification of R&D investments in computer and computer networking technologies with a specific, high priority government mission (national security). It seems that the US government has had difficulties replicating that performance in other areas: perhaps the repeated failures in energy technology R&D and diffusion policy (see e.g. Jaffe, Newell and Stavins (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). But that diagnosis may be overly facile in overlooking that the energy problem involves many distinct scientific and engineering domains, and local solutions that impinge on a variety of local and global environmental systems. Solutions on the use side of energy markets reduce demand through conservation, and therefore do not feed back to present energy suppliers with widened markets. Doubtless more can be done, but the prominent features of this subsystem do not suggest potentialities resembling the mechanisms that have come into play in the information technology revolution.

The last example deals with the case of implementing a countercyclical policy to help financially constrained firms during recession periods. Actually, countercyclical budgetary policy is hard 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. Also, a countercyclical policy means that public deficits should be downsized (to say the least) once the recovery becomes firmly established; but what are the governance mechanisms (or institutions) that guarantee that such downsizing will indeed occur in equilibrium? Possible solutions include the setting up of rainy days funds with an independent authority determining whether the economy is in recession. Also, contingent public debt claims may help achieve better countercyclicality. Finally, using third parties (i.e other countries) to enforce the commitment to reducing deficits. To what extent is it possible to conceptualize a policy as providing one-shot solutions to cyclical problems?

More generally, the design of a comprehensive growth policy requires: (a) that characteristics of the country or sector such as its degree of technological development or the extent of financial constraints, the nature of slow-moving institutions in that particular country or sector, be taken into account by the policy maker rather than propose one-size-fits-all measures; (b) a more systematic cost-benefit analyses whereby, the contribution of each particular measure to the growth potential of the sector or country, and its complementarity to other policies, would be weighed against the (short-term) cost of implementing that policy; this cost-benefit analysis would in turn help the policy maker in establishing priorities in the overall reform agenda. No such comprehensive exercise has yet been attempted to our knowledge, although it now seems within reach given the current state of growth theory and the access to data. However, the two requirements (a) and (b) bring up the difficult issue of institutions in relation to the process of technological change.

5.2 Some tools to enhance the art of managing the complex system dynamics of innovation

The theory of technology policy is pretty 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 technology policy. There is a broad opened research agenda which has to address such implementation issues.

“System dynamics” theory offers a method for understanding the dynamic behaviour of complex systems. The basis of the method is the recognition that the structure of any system — the many circular, interlocking, sometimes time-delayed relationships among its components — is often just as important in determining its behaviour as the individual components themselves. It has been pointed out that there are some features that are especially prominent in STIG and other tightly coupled subsystems of modern economies, particularly non-convexities 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 non-linearities in the responses of agents, or whole subsystems, making it possible that the instabilities created by those feedbacks result in unexpectedly abrupt and discontinuous transitions – formal mathematical “catastrophes” – between markedly different states of the system. Thus, it would be reckless to ignore the potentiality for surprising and perverse outcomes to emerge from what may appear to the unschooled policy-planner 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 regional market or institutions.

Recognizing the possibility that things may go badly awry, without 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 is that is “little bit of knowledge” is likely to encourage policy inaction. Yet, as business decision-makers understand, or come to be taught, inaction is itself a strategy that can be punished severely by unfolding events that are 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 other’s actions can be far more dangerous than experimenting with policies, and especially if one act in ways that are reversible, or subject to subsequent corrective modifications. So, we might conclude that an options-theoretic approach is called for: the expected costs of deferring an irreversible investments that would seize the gains from existing knowledge (in order to collect more information) should continually be weighed against the expected costs of "prematurely" making commitments that will turn out to be mistaken.

This sounds reassuring, but how to assess those costs, and how to identify those situations in which a policy commitment that can be effectively reversed at reasonable costs becomes essentially infeasible to undo? The area of environmental policy is fraught with such traps: lakes that become so polluted that they cannot clean themselves, and so on. The policy can be reversed, perhaps, but by then the action will be ineffectual, or will entail far greater resource costs than were sunk when it was first introduced. Many areas of conventional economic policy exhibit this kind of dynamic asymmetry.[11] It was relatively costless to remove the system of institutional patent agreements whereby U.S. universities could 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, if not from the administrators of some of the Universities that were lucky and smart enough to learn how to benefit from the new regime, then from an entire new profession of university technology managers who have their own professional association (AUTM), complete with a newsletter, offices in Washington, D.C., under plans to open branches in Europe.

Clearly, some among these effects can be modeled in anticipation, and simulation exercises would provide a framework in which to assemble and integrate empirical information about the behaviour of various parts of the institutional, environmental, demographic, and governmental systems that will interact. Moreover, the construction of the apparatus for such modeling exercises will force researchers to pay attention not only to how sub-systems are linked with one another, but to the vital question of the time lags and adjustment speeds that govern the propagation of responses throughout the system. This will expose many of the worst conceits and delusions of policy advocacy that involve abstracting from the question of how long it would take before the promised effects are realized. That will not make getting government ministers and legislators to adopt sound STIG policies any easier, because most of the policies results will emerge much too far in the future to be of immediate political interest. But, at least, it would contribute to clearing the air of the promises that this or this particular legal, institutional reform, administrative rule or tax measure affecting the funding of academic science or corporate R&D, or both, will combat current unemployment, simulate new firm growth, or reduce infant mortality in time for the next election campaign.

6. POLICY EVALUATION AND ASSESSMENT IN A SYSTEMS CONTEXT

A logical complement of technology policy deployment is systematic policy evaluation. A "naïve" policy maker would take the innovative success of a subsidized company as a proof of policy

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[11] The J curve-phenomenon in exchange rates in the U.S. in the 1980's became a familiar example: allowing the dollar to become overvalued opened the country to the penetration of imported consumer durables, notably Japanese automobiles. Depreciating against the yen, however proved unavailing to stem the tide of imports, because the "beach-head" of automobile dealership and parts distribution centers represented high sunk-cost facilities whose owners absorb the higher whole costs of imported vehicles in order to remain competitive in the American market.

efficiency. On the other hand, any success of a publicly funded project says nothing about the efficiency of the public resources allocation process because it is difficult to demonstrate that such success would not have occurred in the absence of any policy. We know that proving causality in a policy area is particularly difficult since it is impossible to assess the effectiveness of the policy implementation by comparing the cases with and without the policy.

6.1 The challenge of the counterfactual

What we do not observe is the counterfactual, that describes what would have been the outcome of the company had it not participated to the program. This counterfactual has to be estimated. One way to estimate the counterfactual would be to compare the innovative performance of a company before the policy and the innovative performance of the company after. However, this procedure would attribute any changes that occurred to be an effect of the policy; a result that would be acceptable only if nothing changed within or outside the company except the exposition to the policy (an assumption that cannot be reasonably maintained).

Another way to estimate the counterfactual is to resort to the population level and compare the average innovative performance for the firms exposed to the policy with the average of innovative performance of the firms that are not exposed. Such an approach, however, is severely limited by selection bias in both of the populations, and matching approaches are devised to mitigate the selection bias. But this too has its limits, inasmuch as “perfect matching” of organisations or individual agents is conditional on identifying a relevant set of control dimensions ex ante, so that unobserved heterogeneities, rather than the presence and absence of the “treatment” could bias the result. Does one know, *ex ante*, which of the unobserved differences are likely to matter, or know enough to find some instruments that would control for the latent variable? Inasmuch as evaluating policy programs is an exercise in counterfactual analysis (Klette, Moen and Griliches, 2000), it has been argued that one of the pressing needs in the economics of technology policy is the implementation of a randomized evaluation designs – for example in evaluating the effectiveness of policy instruments such R&D subsidy programs, or tax credit schemes (Jaffe, 2002).

To some this sounds like a radical departure in the funding of R&D, or in demonstration adoption programs, but it is hard to dispute the general proposition that randomized trials are essential for empirical proof of causal effects. The problem that then must be faced is that arranging such trials in a systems context involves a decision as to what background conditions to set, recognizing that there may be significant systemic effects on the outcomes. Does one test in an optimally designed experimental context, when such is not likely to exist? Or should one do trials to determine which is the constrained, second- or third-best option—rather than the n-best?

But, all that applies at the level of the policy assessment research. What about the political economy of such programs? The fact this proposal has not yet been taken up systematically does not appear to have prompted the advocates of randomized trials of R&D programs pause to think about explaining to the member of parliament, or the Congress-person why the member of the tree pairs of firms that lost the coin toss in every instance were in her constituency, whereas the winners all were in the neighboring constituency; and suppose that party majorities were different in those constituencies? This is only the simplest of problems. There are credible commitment issues: if you run experiments to see if there are positive spillovers from subsidies, in encouraging private investment in R&D –rather than substituting public for private funding. That is all very well if one is running an agricultural experiment station, or trying out a proposed system of auctioning the rights to patents on a particular class of government sponsored research results, or a certain way of organizing primary school in a given city. The experimental strategy is designed to isolate the trial, in order to identify and measure the causal effects.

6.2 The problem of "scaling up"

Now we must consider what this is able to tell us about the consequences of applying the "treatment" throughout the system, to all farms, and all primary schools, or to all government sponsored research. But, partial evaluations at what scale? Giving subsidies to R&D in a small sector that has no specific input requirements can translate into more research volume, whose results can be evaluated. But does that scale? Consider the short run general equilibrium effects on wage rates of researchers of a major program, especially those driven by military considerations: the impact on civilian R&D activities in the short and near-term may be quite perverse..

Further, isolation of the experiment may be able to identify how the results of a given "treatment' will vary with certain features of the environment. However can one do this in the world? What about the other policy interventions that are busy trying to alter the very background conditions that were held constant in order to identify the "dosage" levels of the policy instruments that would yield the best result for the money? Here again, it would appear that the system perspective calls for assembling the findings of partial research within the artificial, and manipulated context of a simulation structure. Policy coordination exercises could then focus on discovering which partially evaluated interventions will be mutually compatible in a global system at least, and mutually reinforcing at best. But that is not all, for the order in which interventions are introduced may be critically important, as the experiences of the Russian and eastern European "transition economies" in some instances made all too painfully apparent. The length of time for individuals and organisations to learn about and adapt to those "innovations" and for stabile behaviours to emerge, is a subject for interdisciplinary social science research that has been neglected, and yet would seem critically important if we are to have evidence-based policies for science, technology, innovation and growth –or, indeed, for anything else.

7. 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 too charged. It is thus critical to try different ways of structuring policy in this area so as to minimize the array of conceptual and practical policy challenges that are entailed. This essay has sought to confront these, by addressing the issue of practical implementation of correcting market failures, and policy coordination failures, of finding an appropriate systems paradigm and (simulation) tools to work within it to assess the dynamics of interactions among policy initiatives, and finally, 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 speaks 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 by exercising a simulation model to learn about certain qualitative dynamic properties of a complex system. But simulation models often remain un-informative about critical determinants of the dynamics of systems of human actors, some but not all of whom pursue adaptive strategies – but not necessarily in all their spheres of activity; moreover, it is a seriously complicating factor to allow for the fact that the policy-decision makers and implementation agents are themselves part of the interdependent processes and may become contributors to destabilizing positive feedback dynamics. Empirical detail will be best 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 not realistic detail, for the art of navigation in the terrain of "political economics" will not be advanced by furnishing either the researchers or the practitioners of policy-setting with "a map that is as big as the country."

The last words are saved for those aspire to become visibly effective agents in "directing" the processes of scientific advance, technological change, and innovation along trajectories so as to contribute to improving economic welfare and material well-being of whole societies and nations. Palpable effects of public agency interventions in STIG processes are not likely to translate into political credits within the time frame within which practical politicians and public servants in representative democracies have to function -- except if their objectives are confined to redistributing claims of resources gathered by taxation among their respective constituencies. In the realms where creating new scientific and technological knowledge and finding ways to use it are essential, the advances are incremental and cumulative, and the assignment of responsibilities for significant successes are retrospective rather than contemporaneous. Moreover, in complex, contingent, and at best partially understood dynamical processes, individuals who hope 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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