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**ABSTRACT**

This paper reflects on the relevance of systems thinking about 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 literatures 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 analyze their respective virtues while also acknowledging their more serious problematic features. Those become visible quickly when trying connect systems-relevant research with practical policy-making in this field. Not content to have simply identified some significant obstructions in the path toward that goal, the paper also suggests some potentially feasible ways forward.

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

## 0. Introduction and apologia

The celebration of SPRU's 40th Anniversary with a conference on *The Future of Science, Technology and Innovation Policy* is perhaps as good an invitation as one may hope to get to revisit familiar and favorite research questions while reflecting on the evolving art of what used to be called, simply, "science and technology policy." We take this opportunity to comment on the relevance of "systems thinking" about interdependent policy issues that bear 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 here, but it is necessary also to acknowledge their more serious problematic features. Those become visible quickly when trying connect "systems-relevant" research with practical policy-making in this field. Not content to have simply identified some significant obstructions in the path toward that goal, the paper also suggests some potentially feasible ways forward.

There is little hope of our being able to do justice within this short conference paper to the implications for policy research and practice of thinking about even the core of the system of *STIG* relationships – that set of interdependences affecting science, technology, innovation activities and their reciprocal connections on economic growth. We also are acutely aware – especially in the present company -- of the limitations of presenting these questions almost exclusively from the perspective of economics. Ours is but one among the relevant disciplines that should be heard from on the subject, but there is reason for us to hope with some confidence for a polite hearing from those expert in other disciplines. They too must eventually seek shelter under Lord Russell's umbrella injunction: the narrowness of specialists is to be forgiven, because they (often) do good work. At the same time, to be able to stimulate (if not provoke) some multi-disciplinary conversations would be especially appropriate on this occasion, if only because much of what we want to communicate draws upon general ideas and insights from "systems theory" – a notably interdisciplinary field, whose founders brought together theoretical concepts and principles from ontology, philosophy of science, physics, biology and engineering.[1]

At least one further and related observation should preface this discussion. The ascendance of a particular kind of "instrumentalism" during the past decade has resulted in an unhealthy narrowing of the focus of public policy discussions touching the production, distribution and utilization of scientific and technological knowledge. Consequently, those who are not concerned primarily with the economic growth objectives of public policy-making in these domains have found it increasingly difficult to make themselves heard in policy research conversations. This is too often the situation regardless of whether or not they have important insights to contribute on the subject of the rate and direction in which "technological progress" and "knowledge-driven innovation" are proceeding in contemporary societies. Because what we have to say here will not qualify even as a gesture towards remedying this state of affairs, it seems all the more important at least to affirm our view: that human welfare and well-being, in the broad sense of those terms, is about many other vital matters besides economic welfare; that even the improvement of economic welfare – with which as economists we are

[1] Systems-theory research, moreover, has found its way into diverse research domains, including many of the social sciences – economics, sociology, political science, organizational theory, and management science, as well as in geography and even psychotherapy (as in "family systems therapy"). For an intellectual history of "systems research" and its relationship to cybernetics, see François (1999). Among prominent economists, Herbert Simon (1962) was a pioneering contributor to the modern theoretical treatment of complex systems.

properly concerned -- cannot completely subsumed under what has come to be understood by the terms “economic development” and “economic growth.”

Further, along with most social scientists, we take economic development and economic growth to refer to processes of transformation and change in large and complex *systems* -- which is to say, in aggregations of interdependent and interacting individual agents, including the organizations formed by their recurrent patterns of interaction, and the formal institutions they may create. In turn, those institutions reflexively shape their creators’ actions and the beliefs and behaviors of successor generations. But, just we may discern economic sub-systems whose performance is a matter of focused (or narrowly construed) policy interest, so too there are “health care systems,” “systems of education,” and “cultural production systems,” and “spatio-environmental systems”. The intricate structures of the latter, and their direct and indirect interactions with the economic sub-system, give rise to important meta-level system complexities. Certainly these could be, and probably should be considered integral elements within the purview of those who study and prescribe public policies affecting the allocation of society’s resources to scientific and technological pursuits. Yet, in this essay barely touches upon that challenge, except possibly to suggest some analogical considerations of suitable research methodologies.

## 1. Re-thinking familiar themes in alternative “systems” contexts: from innovation-for-growth instrumentalism to science and technology policies?

Widespread acceptance of the centrality of technological change and innovation in the process of modern economic growth, and increasing awareness of their intimate and multiple connections with advances in science, therefore encourages the conceptualization of “science, technology, innovation and growth systems” (STIGS) as appropriate subjects for policy-oriented research. This is not new. Incipient formulations of such a program were appearing two decades ago in the focus on “systems of innovation” and “national innovation systems” within frameworks variously proposed by Freeman (1987), Lundvall (1992), and Nelson (1993).[2] The broad thrust of the concept of a system that generated the knowledge that gave rise to innovative activity, and hence to the source of technological change, fitted neatly with the fashionable macroeconomic formalizations that the new, endogenous growth theory was giving to a much older body of thinking about economic growth.[3] The “new growth theory” has both drawn upon and reinforced the strength of the contemporary consensus in the industrialized countries on the promotion of technological innovation as the key goal towards which public policies for economic growth should be directed. The emergence of that analytical and prescriptive nexus has been the strongest and most pervasive single force shaping the current relentlessly instrumental orientation of economists’ enquiries into the structure and functioning of private and public institutions, governmental agencies, and global markets for tangible and intangible resources involved in the production and distribution of reliable knowledge.

A consequence of that orientation, however, has been to transform much of contemporary economic research on those subjects into derived aspects of “technology policies for growth.” The logic goes as follows: the main source of long-run gains in labor productivity and real output per capita is gains in measured total factor productivity -- which is taken to reflect and summarize the effects of “technological change.” The latter is of course a catch-all, that even when most narrowly interpreted subsumes both advances in the frontier of “best practice technologies” (including innovative designs for final products as well as new techniques of production), and the maintenance or actual narrowing of the gap between “average practice” and “best practice.” Although societies

[2] For an early treatment of the policy implications of some aspects of the NSI approach, see David and Foray (1995, 1996). David (1993) considered technological change and its relationship to the growth of research-based and experiential knowledge from a general systems-theoretic perspective.

[3] On that rich older tradition of “thinking about economic growth”, see, e.g., the so-titled volume of papers by Abramovitz (1989). Landmark contributions to new growth models featuring endogenous technological change include Arrow (1962b), Romer (1986, 1990), Aghion and Howitt (1992). Aghion and Howitt (1998) provide a conspectus of this modeling approach, and an elaboration of their early contributions.

may acquire knowledge from external sources, technological progress doesn't fall upon the world like "manna from heaven." Each of the foregoing processes requires investment of resources (somewhere) in the search for knowledge; *a fortiori* for the directed research and development that is needed to make the transition from exploration and understanding of "the way things are" (*logos*) to "the way things ought to be" (*techne*) – the designs and practical engineering implementations of useful and commercially viable innovations.

By working backward through this simple schema, starting from the objective of "greater economic welfare from economic growth," one arrives at derived policy strategies for stimulating the rate of innovation. In this way, a whole array policy actions – including government fiscal measures (taxes and subsidies), the apparatus of statutory regulations and administrative procedures (including public procurement policies and technical standard-setting), as well as legal arrangements for the protection of intellectual property rights -- may be envisioned as being yoked together instrumentally, in a fashion best suited to induce the proper rate of STI-investments that will continue to pull the chariot of "productivity and growth" swiftly upwards. But, those are tactical details that can be worked out by specialists in the respective institutional areas, ideally on the basis of empirical evidence comparing the performance of alternative institutional mechanisms and levels of resource commitment. In this framework of thought, the critical task for economic policy analysts is to determine where the public policy interventions are needed, and where the system of private agents and organizations and the existing structure of inherited institutions should be left to continue functioning undisturbed.

The foregoing quite clearly is intended as something of a caricature. Its exaggerations and simplifications serve, however, to capture key features of the underlying conceptual framework that orders the prevailing economic approach to myriad issues that are engage the attentions of specialist researchers in the science, technology and innovation policy. Rather than being treated in isolation as distinct and separate topics,[4] 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."

### 1.1 The thrust of the argument and the organization of its presentation

Nonetheless, for others, and especially for the more seasoned practitioners in the arts of science and technology policy-making, it is just breathtaking. 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

[4] Treatment of these topics as sub-specialities within a research domain labeled "the economics of science, technology and innovation" would perhaps 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 taxonomic scheme for articles published by the *Journal of Economic Literature*, and used widely for the classification of citations. This peculiar omission poses an interesting anomaly for study by students of the sociology of science. While they are at it, perhaps an explanation would be found for 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 some departments' curricula offer graduate courses on the subject.

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 STIG 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 "systems theory" could serve to guide the prescription of remedies when market's fail? Alternative conceptual frameworks, including those more accommodating to evolutionary analysis of the dynamics of complex systems, may readily spring to mind here, commending 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?

Our discussion of these fraught questions follows a line of argument that unfolds in the next five sections. Section 2 elaborates on what already has been said in caricature of the ways that the mainstream economics literature -- under the dual influence of the "market failure rationale" and an instrumentalist approach that orients policy toward the promotion of economic growth -- addresses policy problems arising from research on the workings of the science, technology, innovation system. The perspective is widened further in Section 3, by explicitly recognizing 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 labor markets, or stability and responsiveness of financial institutions.

Section 4 then takes up the question of the practicalities and costs of actual policy interventions that almost of necessity will have some differential effects on technological research and innovation diffusion at the micro-level where programs, projects and products compete are in competition with one another. 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 behavior 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 Section 5, were 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" by means of stochastic simulation models. Moreover, the use of simulation in this systems context is seen to provide a means of integrating and appropriately "scaling up" particular empirical findings, especially when the latter are obtained (as is now widely advocated) from controlled and therefore necessarily partial studies designed to statistically evaluate specific program structures and policy instruments. The paper concludes in Section 6 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. STIG policy rationales and tools: the field as seen from the economic growth perspective

While studies of the political economy of science and technology policy, and of the sociology of scientific knowledge, and of the "social shaping of technology" have been proliferating and raising skeptical and frankly critical questions about the social desirability of the directions in which scientific and technological research and development are channeled in modern societies, recent economics research addressing science and technology policy matters 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 that have been drawn to enter this area are intrigued by the possibility that the good results observe 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 resources training.

For the most part, however, the resulting contributions to the literature eschew explicit discussion of the allocation of resources for different kinds of discoveries and inventions, or the choices among alternative ways in which new technological capabilities might be deployed. Instead, the style of 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 specifically technological capabilities that under the right economic conditions can generate innovations bearing lower cost or higher quality new goods and services, and 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.[5] 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 enmeshed choices among concrete societal options, and, instead to consider the most generic class of policy problem. This is the issues of whether the right *amount* of investment is being allocated to the production and dissemination of new research results, which 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 modern economic case for policy intervention in this area (as in others) then 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, it rooted in now classic formal statements (almost a half-century ago) 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. More recently, the rationale has been further elaborated by consideration of the implications of innovational complementarities, coordination failures, and to the economics of path-dependent evolution of technologies and institutions. Each of these conceptual developments involves a certain articulation of the market failures approach, and a corresponding search for appropriate policy tools and instruments.

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

Modern economists have followed Nelson (1959) and Arrow (1962) in arguing 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 which 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

[5] We take some care here to distinguish "information", which is conceptualized as "structured data", from "knowledge." The latter we view as a particular class of human cognitive capabilities that can used to gather and filter data, extract information from it, and translate the information-signals into in a variety of actions. This relational schema, and its connections with codification are further elaborated by David and Foray (2001, 2003).

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 Aghion-Howitt (1992)). 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 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 which has to be underscored here is that it is difficult, and generally costly to retain exclusive possession of them whilst putting them to use. Of course, it is possible to keep a piece of information or a new idea secret. But, the mere production of results not achievable otherwise, will disclose that a method exists for doing so. 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.[6]

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, confusions linger around its meaning and implications. It does 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, simply because 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 for -- especially in "arms length negotiations" among parties that do not have asymmetrical 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 the right 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 is invoked in the mainstream economics literature as the primary rationale for the

[6] 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.

government interventions by means of a 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 they would appear to be on first sight.

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

Part of the conventional market failure justification offered for government intervention in the sphere of scientific and technological research and development recognized a difference between exploratory or "fundamental" or "basic research", on one side, and "applied" or "commercially-oriented" research and development, on the other. The special need to subsidize the former was found in its greater uncertainties and the longer time horizons over which research programs of that kind had to be sustained. This line of argument, however, does not adequately account for the existence of two quite different organizational and incentive mechanisms that government support maintained, and worked through in providing economic support for research activities. More recent institutional analysis, associated with the so-called "new economics of science" offers a functionalist explanation for the "open" part of the institutional complex of modern science, which traditionally (and in many countries still is) was 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 behaviors among scientists (Dasgupta and David 1987, 1994; David 1998, 2003). 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, reduces excess duplication of research effort, enlarge the domain of complementarities and yield beneficial "spill-overs" among research programs.[7]

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" have 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 organization) 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 mechanism: rivalries for priority in the revelation of discoveries and inventions induce the

[7] 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.

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. [8]

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, balance the allocation of resources at the macro-institutional level and seeking to maintain both regimes within a single organization are quite different propositions. These alternative resource allocation mechanisms are not entirely compatible within a common institutional setting; *a fortiori,* within 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 Fixing market failures due to the appropriability problem, in theory and practice

Which "repair tools" to use? *Generic* 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 tool for this purpose. Nevertheless, a role is recognized also for direct funding of research conducted by public research organizations (including tax-exempt educational and charitable institutions), and even for contractual procurement of mission-oriented research in support of both civil government functions (e.g., public health services) and defense agencies. 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.[9] Economists' recommendations for non-specific forms of subsidization in this area, happily, find political backer the more readily because it is easier to build a large supporting coalition if the policy prescription doesn't 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. By contrast, subsidy-programs for research promoting technological innovation in particular branches of industry, or aimed at yielding superior (e.g., "environmentally friendly") substitutes for specific resource inputs, are far more likely to encounter concerted opposition from firms that view the intended technological advances as competitive with their established lines of business. Programs that would promote the adoption of particular technological innovations, *a fortiori*, look like interventions that would create losers as well as winners and 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.[10]

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[8] See Aghion-Dewatripont-Stein (2006) for a theory of academic versus industrial research based on control right considerations. In particular this theory rationalizes the role of freedom and its complementarity with openness in academia, by contrast with private sector research where focus is of the essence.

[9] A frequently asserted formula is that "government 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. What is meant by being "a winner" is almost invariably left undefined. The political economy content of this rule is that politicians manifestly prefer being able to associate themselves with those individual successes that can be picked out, *ex post*, among the mixed results of large and diversified portfolio of funded projects.

[10] For this reason, by comparison with "innovation" (i.e. R&D-subsidy) policies, "diffusion" policies have been the "Cinderella of the Technology Policy Ball" – and still waiting to be found by some prince. See David (1986), and David and Foray (1995).

Which "market failures" are to be fixed? From the viewpoint of modern analysts who stress the implications of incomplete and asymmetric information, "bounded-rationality" in decision-making, and the absence of arrangements for contracting with future generations, the whole economy is one large "market failure"…a point on which the laissez-faire advocates and pro-interventionists seem to concur. The former, however, argue that perfect competititive equilibrium is not a relevant standard, so one might trust in the dynamics of competitive entry and restraint on government support for failing enterprise to at least weed out the inefficient and push the allocation of resources in directions that will provide more aggregate goods and services. The liberal-interventionists are inclined to take the view that one cannot trust actual market processes to have that effect, subject as they are to various externalities, barriers to competitive entry, and political distortions – many of which are ineluctable. We appear to be back at "square one." This could be seen as a failure of the "Lionel Robbins (1932) finesse": which tried to find a formula whereby economists could participate in economic policy formation which maintaining their "scientific" respectability. This effort at a clear demarcation between non-subjective analysis and ethical norms and values, greatly influenced the emphasis that economic welfare analysis came to place upon identifying inefficiencies in resource allocation whose corrections could be prescribed without becoming entangled in moral arguments as to whose welfare would thereby be improved.[11]

Even after it had become clear to welfare economists the intervening make only Pareto-improving changes was a defensibly non-subjective ("values-neutral") policy recommendation only when compensation actually would be paid to all of the losers by the winners, the policy rule was recognized to be practical only when there was only a single source of departure from optimality – i.e., when one relative price was out of line with relative marginal costs. But (as the Lancaster-Lipsey "theory of second best" showed), when there was more than one thing marginal equivalence conditions that was not being satisfied, things might be made worse by fixing one of them and actually could be improved by creating another "distortion" of the relative price structure. In this light, perhaps it has not been such a good idea to so good keep economists from systematically learning how best to structure the social and political processes of deciding what to do first, and second, and when and with which industries (or even classes of enterprise) to initiate action in real time.

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. no discrimination in the public funding allocation process among technologies or sectors, so that market signals remain the driving forces for the detailed allocation of investments by private agents and corporate bureaucracies-- and not government bureaucracies that might be more disposed to ignore the market's signals in favor political considerations. Here the neutrality concept is promoted as a basic premise of policy objectives so that the usual problems such as picking winners, government failures, competitiveness distortions, early lock in are mitigated. Of course, an acknowledged and widely approved (or at least tolerated and institutionalized) policy departure from the neutrality principle is seen the provision of differential support to the innovative activities of firms in different ranges of the size-distribution. The economic rationale for making such 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,[12] including those

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[11] By confining government policy interventions to those that would effect Pareto-improving changes: everyone would at least benefits to some extent from the removal of sources of inefficient resource allocation. It was good to instill in economists the professional stance that they had not special qualifications for choosing one rather than another point on the trade-off curve between butter and guns, just because they knew how that curve should be drawn.

[12] - 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 otherwise would create difficulties in translating research into product innovation and

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.

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 research microeconomic resource allocation questions (and welfare analysis issue 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.

Departing from "neutrality" in regard to the specific direction of exploratory research, applied R&D, or the commercialization of technological innovations and their adoption into widespread use is widely seen to be a tricky business for public policy. Obviously, government interventions that are explicitly differential in their intended impact entails 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 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" any particular market will appear to be in the reality of a world that is virtually riddled with market failures – if perfect competition under conditions of perfect information is the benchmark – would involve counterfactual assessment that are 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 filter out other sources of "illumination". Secondly, special interest groups are often the ones with the resources to gather the pertinent economic and technical information required to mount an argument that their chosen "market failure" should take priority others in being remedied. Thirdly, when it comes to appropriations of for subsidy and procurement programs, or the funding of specialized government research institutes and programs, budget constraints force priority-setting and choices that may be difficult to reverse significantly without writing off sunk costs, and reducing the credibility of public policy commitment. Thus the injunction to be "neutral", if it has any force at the margins of decision-making, operates to normalize and privilege the claims of established programs – which in many cases the legacies of previous, glaringly non-neutral government policy commitments.

## 3. Policy complementarities in a larger dynamic systems perspective

The economic payoffs from public programs that aim to promote innovation by supporting private R&D investments are more likely to be disappointing, if indeed they materialize at all, when program design and implementation decision fail to take account of the interdependence of the STIG sub-system with the economy as a whole. Inasmuch as doing so would overwhelming complicate the task of policy design, two pragmatic rules recommend themselves for adoption. The first calls for to separate two notional parts of the larger system: one part represents features and relationships that reasonably can be treated as being only slowly changing or fixed "structural parameters"; whereas the other part is likely to generate feedback effects that are novel and surprising (in either their nature, or magnitude, or in

production—provides a first-best solution for most of these economic problems. Schumpter embraced essentially this view in *Capitalism, Socialism and Democracy*.

both), and are likely to materialize because the policy intervention induces secondary and collateral effects to which the targeted agents and organizations (and the markets in which they operate) are especially responsive.

"Responsiveness" in this context is a matter of whether or not changes happen quickly in real time: "immediate repercussions" from the planned intervention are, for practical purposes, those that will be felt within the time frame during which programmatic commitments cannot be revised (the programmatic "short-run"). Thus, if research organizations would be able reconfigure themselves in order to meet announced eligibility criteria for subsidies, or tax credits, that potential change in the policy's target population would have to be anticipated.[13] To the extent that the system of relationships in the economy is "semi-decomposable", this design strategy allow one not to have to take account of everything, and to separate the immediate design and implementation problem from the question of how "the intended intervention" eventually will affect the system as a whole.

The second analytical principle is related to the first, in that it focuses on the more "tightly coupled" elements and gives 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.

### 3.1 Coordination among Sub-Systems Complementary with the STIG System's Core

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 rather ineffective when attention fails to be paid to the context that is set by policies for educational and training, labor market policies, competition policy, and macro-economic stabilization policies. In the following these areas are taken up briefly, in turn.

3.1.1 *Education*: That education should be thought 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").[14] There is in fact a fundamental complementarity between R&D investments and human

[13] Another illustrative example is provided by considering incremental tax credit schemes, which are award credits on the basis of the change that the eligible firm's R&D investment expenditures from some previous tax period. These generally are found to be more effective in eliciting increase investment than simple tax-rebate programs. But, to the degree that their introduction can be anticipated, they can be "gamed" by firms that defer R&D expenditures prior to the program's launch. High enough marginal credits also could induce stronger positive co-integration in the movements of corporate profits and R&D expenditures, particularly if there is some progressive-ness in the effective corporate tax rates.

[14] The view that complementarities are reflected in differential "catch-up" behaviour has found support in tests based on cross-country panel data: see Benhabib-Spiegel (1994), and Krueger-Lindhal (2001). More recently, Vandenbusshe-Aghion-Meghir (2004) and Aghion-Boustan-Hoxby-Vandenbussche (2005), have decomposed education spending or attainment into "lower- brow" and "higher- brow" educational programs, and shown that growth in countries, and states with the U.S. that are closer to the technological frontier (defined by relative productivity standings), benefit more from advanced (particularly graduate) education than do those farther 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 U.S. and other industrial economies are quite consistent with these econometric findings: see, David and Goddard (2003: Pt.II.3, pp. 71-94) for a review of empirical research on issues of convergence, catch-up and human capital formation.

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 that the educational system has to provide. 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. Endogenous growth theory shows that in order to accelerate growth, it is not enough to increase R&D expenditures. It is rather necessary to increase the total quantity of inputs related to the R&D process (Romer, 2000, 2001).

3.1.2 *Labor market policy:* 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 destruction can be realized (Saint Paul, 2002). These costs are 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. However, in terms of innovation (as entailing creative destruction), the costs of developing new activities will crucially depend on the ease with which "destruction" can be realized.

Thus, the US, with much lower firing costs, will eventually gain a competitive advantage in the introduction of new, innovative products and processes, 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 is based on a fundamental tension between the objective of gaining in competitiveness and the objective in maintaining the social model (Soete, 2002). One should note finally that any evolution toward higher labour market flexibility and lower costs of destruction must be strongly related to the development of *life long learning capacities*. Easy destruction is socially acceptable and economically efficient only if individuals have acquired the capabilities to confront constant changes and to transfer their skills from one learning setting to another. Now, 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, may require active labor market policies of the type pioneered in Denmark. These in turn are costly, hence the importance of adequate macroeconomic management.

3.1.3 *Competition:* R&D subsidies are of little help if competitive pressure 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, 1999), and Aghion et al (2005)) 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) points to a positive effect of entry threat on incumbent firms' incentives to innovate. In the absence of true product market competition, R&D subsidies may end up being used for other purposes including as barriers to entry, by incumbent firms. For example, Aghion-Fedderke (2006) just found that manufacturing firms in South-Africa had mark-ups that were 50% higher than in the corresponding sectors in other countries, and that higher (past) mark-ups were negatively correlated with future growth in South-Africa.

3.1.4 *Macroeconomic policy:* One feature of private R&D investments is that they are very sensitive to economic cycles. They are uncertain, long term and they involve sunk costs. It is therefore obvious that firms will cut them when they are confronted to liquidity shocks, in the context of imperfect capital market. When countries have a low degree of financial development, no financial mechanism exists to help firms to overcome the financial constraint and to maintain innovation capacities. Proactive policies – involving public spending, defence spending, direct subsidies to private R&D, public procurement - are therefore necessary to maintain private innovative activities during the recession period. In such set of circumstances, countercyclical budget deficit is growth enhancing. 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 not a framework in which budgetary policies could be developed as countercyclical mechanisms. The US case shows just the opposite, in spite of the fact that the US is more financially developed than the EU. A recent study by Aghion and Marinescu suggests that growth in the EMU area could increase by up to 0.7% if public debt growth became as countercyclical as in the US.

For all of these issues, the big mistake is to concentrate on a single policy measure while ignoring other policies that could be inconsistent with R&D policy objectives. Policy complementarities, however, raise difficult problem of coordination among different policy objectives: countercyclical budgetary policy is hard to get right on purpose than by accident. A countercyclical policy means that public deficits should be downsized once the recovery becomes firmly established; but what are the governance mechanisms (or institutions) that guarantee that such downsizing will indeed occur in equilibrium?

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.

### 3.2 Institutions and human organizations: limits plasticity, power, and evolution

Institutions and organization engaged in the creation and transmission of technological knowledge, like institutions for other purposes are neither fixed nor exogenously determined. The 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 organizational 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 economics rents being enjoyed by agents within them – although not necessarily by all the agents. 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 – and not only incremental adaptations, for discrete technological innovations are more likely to be perceived as having seriously “disruptive” potentialities. Conglomeration is another strategy that may serve similarly defensive purposes: institutions sometimes find it attractive is to take on new functions that actually do not have strong complementarities with the core functionalities and deeply embedded routines of the organization, yet provide additional access to resources, including coalitions of convenience with other entities.

Yet, being resistant to disruption of their learned internal routines, and on that account less plastic, 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 the 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 organization, or dissolved and supplanted by newly created institutions (David 1994). The policy need to pay greater attention to, worry about, and try to better understand institutional performance and the dynamics of institutional change is obvious, in that they affect the workings of markets, because actual markets are embedded a matrix of formalized regulations and institutionalized conventions. “Market failures” may be traced to obsolete institutions or perversely functioning procedures. Non-market institutions and organizations, i.e., those whose resource support is not drawn from their ability to sell goods and products to private parties 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.

### 3.3 Institutions: system structures or policy instruments, or both?

The economic case for "reforms" of institutions that directly affect the performance of the STIG-system therefore separates into two branches: interventions to change institutions that are seen to be contributing to the inefficient outcome of market-directed processes, and reforms in the internal organizational structures and incentives of public institutions that perform badly in delivering services through non-market channels. In as much as the research and training "products" of public sector research organizations, including government institutes, universities, polytechnics and the like, are not priced and distributed through market channels, the criteria for determining where and when to make targeted interventions are vague, and tend to be arrived at *ad hoc*. Being readily tied to the appropriation of public funding, the policy models then to be drawn from the organizational management, with the main tactical issues being the choice between decentralized guidance with well defined incentives and performance targets, or centralized "command and control." General insights from the economics literature on organizational design (see e.g., Sah and Stiglitz (1985, 1988)) suggest that where the program involve high inputs of specialized expertise, where information on which resource allocation should be based is not symmetrically distributed, and activity planning is highly contingent on the uncertain outcome of sequential production stages, decentralization of agenda control and flat organizations are preferable. This principle seems a reasonable rationale for the large "national innovation systems" that feature a multiple public (and subsidized private) research and training organizations, including research universities. 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 economic support.

There are many cases in R&D organizations and technical changes where institutions have been negatively affected by vested interests and need to be "improved". We would need another paper to fully develop some cases of path dependent evolution of institutions leading to inertia and/or ill-adaptation between the institutional framework and the organization of R&D and innovation activities. Well known cases today involve the intellectual property right system, the institutional framework supporting university-industry research relations in the US and in some other countries and the educational infrastructure. In all these cases, institutions exhibit endogenous dynamic, strongly shaped by initial conditions and some transient events, leading to a mode of operation that can be very far from the "ideal" mode which represented the reason for the initial institutional creation. The patent system is a clear case in point.[15] "Institutional policy" is thus just as important as other classes of government interventions that figured more prominently our discussion in Sections 1 and 2, but institutions are neither technologies nor commodities, and while economists have much to contribute by analyzing the internal incentives and rule structures of specific existing organizations and institutions, and have developed techniques for evaluating alternative mechanism designs in similarly concrete situations, the present state of economic research on institutional dynamics offers few if any general, *a priori* points of guidance for policy reformers who seek to simulate innovation, say, by reforming intellectual property law, or the workings of patent offices, or the organization of research universities. Development policy approaches, which involve some immersion in the local culture and a grasp of the inherited constraints on melioration of dysfunctional performance—without disrupting the routines that permit continuing fulfillment of vital functions upon which external agents and agencies relay, seem the more practical route to success.

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[15] On the historical evolution of the patent system, see, e.g., Long (1991), David (1993), Dutton (1984), MacLeod (1988); and on more recent institutional trends, David (2006).

## 4. STIG policy for complex systems – between coordination failure and excess momentum

While the inability of private agents to coordinate their investment plans in order to create mutual positive externalities and increase both private and social returns from their respective innovations has always been central in historical periods of technological transitions, the perception that such inability reflects a market failure and should require a policy response is rather new. 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 complementarities play a major role in determining the motivation for and the performance of decentralized private investments in R&D and the deployment of technological innovations.

It is attractive to think of using the structure of micro-level incentives created by complementarities in technical systems and organizational mechanisms to amplify the effects of key policy interventions in order to propel the economy, or some large sectors therein 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, should be the recognition that such "levers", such they exist, are likely to be few and far between during any reasonable policy planning time span, and they will be recognizable also by policy-designers in other economies. Success, and especially comparative success pursuing such a strategy, therefore, is likely to turn on something else than mere identification. That "something else" is precisely the capability of those responsible for managing this kind of public policy intervention to anticipate, and avert coordination failures that otherwise would prevent formation positive-feedback dynamics in a "virtuous spiral," rather than the opposite.

### 4.1 Averting and fixing coordination failures, in market and non-market allocation processes

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 cases for 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. 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 was political 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 static, one moment in time 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 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. Understanding the basic principles of coordination problems does not take 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 possibilities for government policy to correct coordinating problems 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 tend to trivialize the coordination difficulties that face policy makers. Inn 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 such 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 effective 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 can an 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 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.

### 4.2 GPT's: "Levers" for technology policy programs to lift the economy's growth rate?

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 a striking case of the appeal of *pars pro toto* devices in policy thinking -- substituting a part for the whole, with all the attendant opportunities for logical and analytical confusions that surround the use of such rhetorical strategies. The technical term for such linguistic devices is "metonymy" – taking a familiar and widely understood aspect of something, and using it to stand for the entirety. What is it, then, that technology policy-makers properly should understand and communicate to others about GPTs? Shall we say it is the technical properties of some specific inventions, like the electric dynamo, that make them "complementary" with a wide variety of other technological artifacts in numerous many uses, and so give the particular technology a "general purpose-ness?" Was it this special quality that held the key to the "dynamo revolution" that ensued in the industrialized economies during the half-century after 1880?[17] Should we think of this GPT as endowed with "quals" that induced investments in the design and construction of electrical supply systems that efficiently distributed power to turn secondary motors and thereby opened the path for further induced

[17] For discussion of the electric dynamo and other "general purpose engines", and the modern significance of the historical experience of these GPTs, see, e.g., David (1991) and David and Wright (2003).

investment in the creation and implementing of new power applications for illumination and mechanical transformations, leading ultimately to the reorganization of production and consumption activities throughout the economy? The modern policy import of such a conceptualization is that one should begin now for look at candidate technologies that will be the 21st century's GPTs.

Alternatively, one may regard the process of "electrification" ---as just described—to have been an emergent property of particular socio-technico-economic systems, those that proved able to self-organize themselves in different ways and by varying means, around a novel artifact, starting with a somewhat less energy-inefficient dynamo design introduced by Edison at the end of the 1870s? The GPT appears from this *non-teleological perspective* to be a creature whose uncommon characteristics were fashioned by the system and its properties, rather than the other way around.[18] Should one then try to identify promising new GPT "targets" towards which the whole economic system (a country) can orient R&D, skill development, financial and entrepreneurial capabilities, in order to avert falling private and social rates of return on tangible and intangible investments, and an ensuing slowdown of productivity advances – either in absolute terms or in relationship to other regions who are competitors in world markets? There have been historical situations that demonstrated that it is feasible in some cases for private enterprise to organize so as to internalize the positive effects of complementarities among specific new technologies, and among fields of application of an emerging technological system, In this way it is possible to form large "industrial development blocs" – such as those in the coal, iron and steel, heavy chemicals and rail transport "empires" of the late nineteenth and early twentieth centuries – that yielded not only high current rates of return, but raised prospective yields from the search for new complementary inventions. But achieving "internalization" of that kind is not automatic or easy, even when the financing for it is available. The potentialities for discordant expectations and coordination failures argue for pro-active, government interventions to push the process of complementary capacity building and initiate some initial market-driven mobilization of mutually reinforcing investment decisions.

This presents an attractive case for government intervention, but not so much because there are areas of technological research that are "hot", and where those engaged are enthusiastic about commercialization opportunities that will eventually be forthcoming (biotech, nanotech, synthetic biology, and so on). The critical property that should be present, if the GPT rationale is to be invoked at all, is that the dynamics of development and diffusion are likely to be characterized by strong innovation complementarities between inventions and the "co-invention of applications." In such case, if the existence of conditions in which that will be the case also makes it likely that if the R&D, innovation, and preparations for commercial deployment are left entirely to the workings of markets and private enterprise, the process is likely to end in numerous failed or disappointing investment projects. The consequence, moreover, is not simply delays, for the feedback effects can work to impede attaining a self-sustaining scale for the technology to become more and more widely deployed throughout the economy.

In the case of IT 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 contributes to economic growth, Bresnahan (2003) stresses that the phenomenon of socially increasing returns of scale that is manifested at the economy-wide level rests

[18] Strictly, then, we should say that in such usage the dynamo-GPT appears as a *synecdoche* for electrification, a part of the process that is being taken to refer to the whole The word synecdoche sometimes is taken to be just a specific sort of metonymy, but the text suggests making an absolute distinction in the present context, because the part (the dynamo) is not simply "associated" with the whole process (electrification), but is evidently one of its elements.

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 to alter the boundaries of business enterprise, alter the nature of market competition, 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 throughout an extended time-span. But, 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 technical interrelatedness of investments, which can result in investment coordination failures due to the limited capability of enterprises to gain access to financing, and control of assets necessary to internalize the key dynamic externalities. Early user's experience is an externality, spilling out from pioneer users to late 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 of 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 corresponding more difficult to prescribe than those discussed in connection with cases involving essentially isolated "market failures" (in Section 2). They are closer in nature to the strategies for designing coordinated policies interventions in product and factor input markets which are closely coupled with scientific research and market-oriented R&D (as discussed in Section 3). 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 labor 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.[19]

[19] 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.

The policy design problem is more challenging both because issues of timing are more delicate (and yet the dynamic processes themselves are fraught with uncertainties), and because it cannot ignore the engineering 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 compatibility, as these permit the realization of economic complementaries and fruitful market and non-market interactions among organizationally and temporally distributed researchers, inventors, innovators, and end-users. Anticipatory standard-setting are 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)). But, there are effects also on the nature and direction of research and inventive activity. The existence of *de facto* industry standards, and specifications set 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 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 an a Schumpeterian competition for the whole market.

Approaching this policy choice as one that calls for attempting to find the 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), would follow a "golden mean" policy principle. The latter is familiar in economic analysis of such situations, but it supposes the existence of "an interior optimum" in the weight that is to be distributed between the two "pure" strategies: push standards or don't push standards. But, as David and Rothwell (1996) show, there are some realistic industrial conditions under which either of the pure strategies dominates intermediate, or "mixed strategy" solutions to the policy optimization problem. That, however, is not to say that standardization policy for technological fields and the industries based upon them should be in a stationary, once-and-for all fashion. 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 are appropriate for the earlier stages, but eventually should be supplanted by a restricted range of specifications that support the technical compatibility and interoperability of system components, and broaden applicability of subsequent incremental innovations.[20]

Such a policy has two clear characteristics: first it is not particularly innovative in the type of tools which are used (actually this is the menu of policy instrument already listed 3. 1); second these tools are activated in a coordinated ways, and are targeting some particular technological fields. Clearly, such a policy departs from neutrality because specific technological and innovation projects will receive particular supports. Many controversial issues are at stake here: the neutrality principle being abandoned, such a policy may create distortions in the resource allocation process by minimizing the role of the market in selection. This view, however, fails to accurately recognize the

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[20] 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 can be viewed an instantiation of a more general stochastic "lock-in" problem that has been analysed by Cowan (1989), and which figures recurring in the literature on path dependence on technological systems (see David 2001, 2005).

historical evidence of many publicly subsidized science and technology breakthroughs that turned out to have significant commercial and productivity payoffs. Recent history of technology policy in OECD countries have shown that such strategic capacity (involving non neutral public interventions) has been a key factor notably in the building of the US leadership in the high tech economy. Comparisons between some good and bad historical experiences show that the very design of the policy as well as its harmony with competition policy play significant role in mitigating some of the potential drawbacks of such non neutral public programs[21]. In this perspective, the best practices seem to be seen in the US federal policy implemented to build the knowledge infrastructure and stimulate private R&D investments in the high technology economy (National Research Council, 1999, Blumenthal, 1998, Mowery and Simcoe, 2002).

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, 2001) 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 who have greater potential to reveal promising options, would be to delay the formation of pre-mature adoption bandwagons, checking the formation of irreversible inter-locking investments commitments so that more information could emerge from the symmetric competition of variant technological designs.

### 4.3. Some tools to enhance the art of managing the complex system dynamics of innovation

"System dynamics" theory offers a method for understanding the dynamic behavior 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 behavior 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

[21] The ingredients of the US strategic capacity are known. It involves a diversity of public agencies; all working on specific but overlapping agendas; a key role for the Department of Defense (DoD) showed both in the history of Internet revolution and, recently, in information security R&D programs launched after September 11. In both cases the impact of government-sponsored research was great in building the knowledge infrastructure in particular areas, generating spillovers to the benefit of the industry (including SMEs), creating incentives for business R&D to respond positively to this policy and initiating market development through public procurements.

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 a present 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.[22] To take another, institutional example: it 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 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 behavior 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, and sub-subsystems are linked with one another, but to the vital question of the time lags and adjustment speeds that government 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 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.

## 5. 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 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

[22] 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 open the country to the penetration of imported consumer durables, notably Japanese automobiles. Depreciating against the yen, however proves 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.

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.

### 5.1 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 which 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 organizations 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 (Colette, Moen and Griliches, 2000), it has been argued that one of the pressing needs in the economics of technology policy is thought to be 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-the 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.

### 5.2 The problem of “scaling up”

But 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.(See Goolesbee (1998), David and Hall (2000)).

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. But 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 organizations to learn about and adapt to those "innovations" and for stabile behaviors 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.

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

Technology and innovation policy for growth is widely accepted, but 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, it immediately become is politically controversial. 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 this essay has sought to expose by addressing the issue of practical implementation of correcting market failure, and coordination failure, 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 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 to 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 methods are not informative for systems as complex as those with human actors, and in which the policy-decision makers and implementation agents are themselves part of the interdependent processes. 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, in order to quantify some dynamical relationships that are believed on analytical and experiential grounds to be critical in rendering the simulations able to providing robust insights that would 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 equally unjustified) outcomes that were unanticipated and unwanted.

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