TECHNOLOGY, R&D, INDUSTRIAL, AND SCIENCE POLICIES: PRIVATE AND PUBLIC SECTOR INTERACTIONS THAT ENCOURAGE TECHNOLOGICAL ADVANCE

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ABSTRACT

This paper distinguishes four types of public policies that seek to encourage growth-inducing technological advance: technology, R&D, industrial, and science policies. The first three are typically treated under the single heading ‘industrial policy’, which is a source of confusion since each is administered by different agents and often with different objectives. Evidence of successes and failures of any one of the policies defined here is often incorrectly taken to apply to the other policies. Evidence for the symbiotic relation between the public and the private sectors is outlined, although typically ignored by in formal growth theories. The massive influence of science policy on economic growth, also typically ignored by in growth theories, is a largely unintended byproduct of scientific advance. A policy implication of the approach in this paper is to stress science, technology, and R&D policies, putting much less stress on industrial policy as defined here.

Key Words: Industrial policy, science policy, technology, economic growth, R&D.

JEL Classifications: 023, 025, 035, 043.

TECHNOLOGY, R&D, INDUSTRIAL, AND SCIENCE POLICIES: PRIVATE AND PUBLIC SECTOR INTERACTIONS THAT ENCOURAGE TECHNOLOGICAL ADVANCE [1]

Technological advances are a key determinant of growth in living standards over time. However, investing in new, unproven technologies involves risks as well as potential rewards. Recognizing this dilemma, governments have struggled to craft policies and incentives that yield social benefits without incurring excessive costs. In order to identify promising approaches, this paper distinguishes four types of public policies that encourage growth-inducing technological advance: technology policy, R&D policy, industrial policy, and science policy. It is common for economists to treat the first three under the single heading industrial policy. It is argued here that the failure to distinguish among the first three has led to confusion since each is administered by different agents and often with different objectives. Evidence of successes and failures of any one of these three policies is often incorrectly taken to apply to the other two.

One of the most important sources of economic growth is the symbiotic relationship between the private and the public sectors–the latter operating through the first three of the policies listed above–to promote technological advance, something that is largely ignored in theoretical models of economic growth, although not in the treatments of economic historians. Also largely ignored by formal growth modelers–and also often by students of industrial policy–is the importance of science policy in creating the kinds of opportunities for the technological advances that drive economic growth.

Section 1 outlines some important definitions and distinctions. Sections 2, 3, and 4 deal with the first three of the above-mentioned policies. Since there is much literature on each of these, the treatment here is illustrative rather than comprehensive. The main purpose here is to show that they need to be considered as distinct policies rather than being treated as a single industrial policy. Section 5 considers some of the arguments of those who deny the importance of these three policies in influencing technological advances and hence economic growth. Section 6 deals with science policy. Section 7 concludes with a discussion of some of the policy implications of the approach taken in this paper.

1. DEFINITIONS AND CONCEPTS

Although there are many factors that influence economic growth, such as institutions, infrastructures, and human capital, technological advance is a necessary condition in the sense that if an economy's technology remained constant, growth would eventually peter out, ushering in the classical economists' stationary state.

This paper follows Carlaw and Lipsey in separating all agents into two groups: those in the for-profit sector (FPS) are "…individuals and organisations operating in pursuit of market incentives such as profits, sales, management earnings, or other similar economic objectives…" (p 8); and those in the not-for-profit sector (NPS) who are all the agents whose motivations are

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[1] This is a major revision of a paper posted some time ago under the title: "Private and Public Sector Interactions that Encourage Growth-Creating Technological Advance. I am indebted to Edwin Blewett, Kenneth Carlaw, Gregory Dow, Herbert Grubel, Jonathan Kesselman, Clyde Reed, John Richards, and Craig Riddel for comments and criticisms on earlier drafts of this paper and to Joanna Lipsey for untiring editorial assistance.

other than those in the FPS. These two groups are often defined as being in the private and public sectors of the economy, but the terms ‘for-profit’ and ‘not-for-profit’ provide a more useful distinction by dividing agents according to their motivations rather than their legal status.

Carlaw and Lipsey also divided the invention and innovation of each new technology into four overlapping stages: invention, efficiency, applications, and diffusion. These stages are hereinafter collectively called technological advances.

What is usually called industrial policy is here divided into three separate policies and a fourth, science policy, is added.

Technology Policy is defined as anything that seeks to encourage the various stages of specific technologies, such as solar and wind power, or longer-lived batteries for electric vehicles.

R&D policy is defined as any policy that seeks to encourage technological advances by encouraging research and development either in particular directions, such as reducing carbon emissions, or in general by encouraging all forms of R&D through such means as tax relief and subsidies. It is not technology policy because it does not single out specific technologies for support and it is not industrial policy because it does not single out specific firms or industries for support.

We need to distinguish two concepts of industrial policy. It is defined in this paper as any policy that encourages specific domestic firms or industries through means such as subsidies and trade restrictions. This is a narrower definition than the one usually found in the literature that includes industrial policy as just defined plus technology and R&D policies. When we need to distinguish between the two, we will refer to *industrial policy narrowly defined* and *industrial policy broadly defined.*

Importantly, both types of industrial policy can have many different objectives such as: (1) punishing a foreign country, or increasing national security, by reducing dependence on some key import and producing more of it at home, even if that increases the cost of producing that product; (2)) greening the economy by such means as encouraging the replacement of fossil fuels by renewable energy sources; and (3) encouraging domestic firms and industries thought to contribute to economic growth. When considering the efficacy of industrial policies, it is important to distinguish among successes and failures in achieving each of its many goals such as those listed above and to realise that failure of a policy to achieve one specific goal does not necessarily imply it will fail with respect to achieving a different goal. This paper is concerned with this last of the above listed motives and, unless otherwise qualified, industrial policy, refers herein to the sub-set, *narrowly defined, growth-inducing, industrial policies*.

Science Policy is defined as any policy that seeks to advance scientific knowledge, such as the search for the Higgs Boson or more powerful forms of particle accelerators. The motivation for these policies is almost exclusively to advance scientific knowledge. The myriad commercially viable new technologies that they often enable are typically unintended by-products.[2] .

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[2] As with many distinctions among related topics, there is some overlap among these four: R&D Policy is sometimes directed at encouraging one specific technology; Industrial Policy is sometimes directed to a specific industry that is

2. TECHNOLOGY POLICY

Examples of agents administrating technology policies are government departments, government-financed research units, NGOs, universities, and non-profit granting bodies that finance technological developments taking place in the FPS.

Many recent studies have established that the NPS has played a significant role in the development of many, probably most, of the major technologies developed over the last 100-150 years. For example, Ruttan (2001), demonstrated that "…the public sector had played an important role in the research and technology development for almost every industry in which the United States was, in the late twentieth century, globally competitive." (as quoted in Ruttan 2006 p viii)

In the same vein, Mariana Mazzucato provides case studies in which the NPS and the FPS were partners in the development of new technologies. For example, in a fascinating case study of the iPhone, often thought to be a prime example of purely private enterprise, she shows that Steve Jobs' genius was in combining into a new product several technologies recently developed by the NPS. She also shows that this iPhone case is typical of many other cases of technological advance, including the internet, biotech, and even shale gas "…in which the State plays the pivotal serious role of taking on the development of high-risk technologies, making the early, large and high-risk investments, and then sustaining them until the such times that the later-stage private actors can appear…" (p 118)

Other writers who have reached similar conclusions about the symbiotic relation between the NPS and the FPS include Lazonic and Leslie. The latter author argues, according to Mazzucato, (p 69), that Silicon Valley has been "… difficult to copy, because almost every advocate of the Silicon Valley model tells a story of single 'freewheeling entrepreneurs and visionary venture capitalists' and yet misses a crucial factor: the military's role in creating and sustaining it."

Carlaw and Lipsey study the development of nine important individual technologies, and one group of technologies, all of which received significant NPS assistance and all of which contributed directly to economic growth.[3] They do explicitly what many other researchers have only done implicitly, if at all, which is to show in which of the four stages listed in Section 1, NPS agents exerted a significant influence, either through financial or direct physical assistance on the technologies they study. Their ten cases are: the internal combustion engine, refrigeration, railways, automobiles, aircraft, agriculture, iron steamships, electricity, computers, the Internet, and lasers. The final four on this list received assistance during all four of their development stages. A few of their many conclusions follow.

- By examining how research and development (R&D) is financed, rather than where it takes place, the authors show that the role of the public [NPS] sector is much more pronounced than is often thought. The nature of the cooperation–who

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seeking to develop one specific new technology and Science Policy is sometimes directed at the science underlying some hoped-for new technology, particularly when developed in such hybrid institutions as Bell Labs. Nonetheless because each of these policies is usually administered by different actors having different expertises and often different objectives, the distinctions are valuable.

[3] Carlaw and Lipsey call their monograph *Industrial Policy.* But the majority of the cases of NPS assistance to the ten technologies they studied fall into our classes of technology or R&D policies rather than our industrial policy.

does what–varies with the nature of each innovation so that simple, one-size-fits-all rules about what each sector should do are suspect. (Abstract)

- "In some cases, the NPS agents need to provide a demonstration of a technology's viability ('proof of concept') before FPS agents are willing to finance further developments towards commercialisation. In other cases, the relationship operates in reverse, with FPS agents demonstrating technological viability before the NPS is willing to finance a significant amount of the technology's further evolution." (p 72)
- "NPS support for emerging technologies can often remove some of the uncertainties that discourage FPS support." (p 73) Where commercial applications are obvious and fairly immediate, NPS support is generally not needed once the concept has been proven. However, as is so often the case, although it is clear that there will be commercial applications, these are more distant and their exact nature uncertain. In such cases NPS needs to support the early stages until the uncertainty is greatly reduced once the future developments have become more obvious.
- "The more a technology depends on science, the larger the place for NPS support for the relevant …[stages]." (p 73)

Although the NPS's contributions are often concentrated at the early stages of the development of a new technology, this is not always the case as mentioned in the first bullet point above. As Carlaw and Lipsey show, sometimes NPS support comes during later stages in the development of a new technology. Indeed, at the extreme, it may be mainly the provision of infrastructure that is needed for the full exploitation of the technology. For example, automobiles were developed almost exclusively by the FPS, while the main direct contribution of the NPS was to provide the infrastructure, paved highways, bridges, etc., without which the automobile could not have reached anything like its full potential.

Economic historians have pointed out that many of the innovations that have raised productivity came in later stages of the development and diffusion of new technologies. Agents, working wholly in the FPS, made incremental changes that collectively added up to big changes in productivity. This might suggest that NPS support has been less important in assisting economic growth than has been argued above. But these incremental changes in the later stages of the development of a new technology could never have happened if the early more fundamental stages had not happened first. For example, it is doubtful if the invention of the dynamo, that was critical in making electricity available in usable form, directly increased productivity and economic growth. What it did was to permit the development of myriad technologies that used electricity. Thus, if some agent in the FPS contributed to economic growth by improving the operation of existing refrigerators, this could never have happened unless generations of agents operating almost exclusively in the NPS had not done work that led over several centuries to the development of commercially viable electricity.[4]

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[4] An account of the "nearly 300 years of cumulative research into all of its [electricity's] aspects to complete the West's research agenda of understanding electricity and magnetism..." is in Lipsey, Carlaw and Bekar pp 254-55.

3. R&D POLICY

The agents for R&D policy are almost exclusively government bodies. As already observed. R&D policy can be directed at encouraging R&D in specific applications, as illustrated by the US Chips and Science Act[5] and the US Department of Défense's (DoD)'s purchasing policies discussed in Section 5 below, or it can be directed at supporting R&D in general. The main intellectual justification for this latter approach is Kenneth Arrow's famous article. It is unnecessary to go into the details of his subtle analysis here. Instead it is merely observed that because the social benefits of most new technologies greatly exceed the private benefits to their innovators, there is a strong argument for policy intervention to cause R&D expenditures to exceed what FPS agents would produce.

The argument for generalised encouragement of R&D through tax relief or subsidies (collectively called assistance hereafter) relies on the neoclassical model where there is perfect knowledge and risk but no uncertainty. Private firms can then be relied on to allocate R&D to the lines where the expected value of its private payoff is highest. Uniform assistance for all R&D will not distort its allocations away for these best lines. However, this argument has problems even in its own terms.

It makes sense only if the external social value is equal in all lines of R&D, which is manifestly untrue. Clearly, for example, the social value of electricity vastly exceeds the private return to those who first developed it and is much larger than the social return of, say, the washing machine. If the relative social values were known, one could adjust the R&D subsidy among firms to maximise its expected social value. Giving equal R&D assistance to all lines of endeavour is the best policy in the neoclassical model only if the social values in all lines are equal.

Going beyond the neoclassical model, the dynamic world in which we live is replete with many uncertainties and open-ended social benefits that often extend into the indefinite future (e.g., electricity). In this case, the concept of a static optimal allocation of the nation's resources, including R&D, makes no sense. In this dynamic world, scientific discoveries often reveal that there are possibilities of commercial spinoffs but it is uncertain what they will be, how long it will take to develop them, and whether the private payoff will exceed the private cost. But the firm that is doing R&D to develop a fairly immediate possibility gets the same assistance as a firm that is working for a distant and uncertain result. In contrast, directed R&D assistance and technology policies can be focused on the latter rather than the former, which is typically what is done.

Of the four policies distinguished in this paper, there is probably more overlap between focused R&D and technology policies than any of the others. These two are indistinguishable when the supported R&D is directed at developing some specific technology. But they are distinguishable when the support goes to R&D in a particular area such as bio- or

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[5] Although often referred to as an industrial policy, the Act's main purpose is to greatly reduce the dependence of American industry on chips produced elsewhere by transferring production to the United States, which is not primarily a growth-inducing policy. It is clear, however, that the designers of this policy have learned the lesson that a fostered industry needs to be technologically dynamic (see below) because a significant amount is allocated to financing R&D and not just to setting up chip-production facilities similar to those currently existing abroad. This is R&D policy in our classification scheme.

nanotechnology, where it is clear that new growth-inducing technologies will be developed, but it is unclear what their specific natures will be or which firms will develop them.

Although in their important paper, Réka, Lane and Rodrik are mainly concerned with industrial policy, they devote their Section 4.6 to R&D policy. They note several empirical studies of what they call "moon shot technologies...the US government's massive R&D efforts during WW2 and the Apollo mission in the 1960s..." They conclude (p 24):

> "Rather than crowding out private R&D, a number of papers suggest the opposite: the potential for public R&D to crowd in private innovation. Similarly in times of national crises, the US government seemed capable of picking technologies, places and firms that could deliver the desired outcomes, often with long-lasting positive local effects."

4. INDUSTRIAL POLICY

Agents for industrial policy are mainly governments in the form of legislatures, government departments, and government research bodies. As broadly defined these policies can have many different objectives. Also, they have a long and chequered career with their results running the whole gamut from spectacular successes to dramatic failures. As observed earlier, this paper is concerned only with a subset of industrial policies that are narrowly defined and growth-inducing.

Juhász, Lane and Rodrik deal with broadly defined industrial policies. They survey much of the literature, including modern attempts to test the efficacy of such policies through statistical analysis. Interestingly, most of the successful policies they survey fall outside of our narrow definition. These include policies to encourage the generation of solar and wind power and production of new non- (or reduced) polluting products such as electric cars.

Many early successes of growth-inducing industrial policies occurred when the countries that are now industrialised, developed their early industries behind strong tariff protection. Even Britain, the country that came closest to free trade, protected its clothing industry by banning the importation of Indian cotton goods.

Later when developing economies sought to emulate these early successes, the problem was viewed from a static perspective. As a result, many growth-inducing industrial policies attempted to establish firms that resembled those currently found in the already advanced countries. The firms were to receive tariff protection until they had expanded sufficiently to reach the low point on their static, long-run average cost curves. Furthermore, a firm was often chosen as a national champion and given access to a fully protected home market. The firm often then chose to collect economic rents, avoiding the uncertainties associated international competition.

In more modern times it has become widely accepted that technological advance is an important tool of inter-firm competition in markets that are not perfectly competitive (as is the case for most markets for manufactured goods). Thus industrial policies designed to establish new firms or new industries must not seek to establish those that are just like the ones currently in more advanced countries. Instead, firms must be able to develop the R&D capacities in order to stay abreast of new developments and thus remain internationally competitive over time—a dynamic rather than a static view of the behaviour of economies.

One of the most spectacular successes of 20th century industrial policies where this dynamic lesson had been learned was the rise of the Japanese automobile industry after the Second World War.[6] A little later, South Korea also created a successful and innovating automobile industry from scratch with substantial assistance from the NPS. With cooperation between the NPS and the FPS, the Taiwanese created their own electronics industry in spite of having no obvious comparative advantage in electronics. The government of Singapore devoted substantial funds to early discovery of emerging technologies and, as a result, developed its own software industry that became internationally successful.[7] In all of these cases the initial developments came from adopting and adapting technologies that existed elsewhere, although later the new industries became leaders in new technological developments.

In these modern cases emerging industries were initially protected. They were, however, usually encouraged to engage in international competition once they were established. Often their support was contingent on eventual success in international markets.[8] This is one way in which other country's failures in similar attempts were avoided.

Other successes of growth-inducing industrial policies are documented in Lipsey and Carlaw (2020). To set against these, however, is a long list of government failures. Here, for example, are a few of those listed by Lipsey, Carlaw and Becker:

> "…the French attempt to build a successful micro-electronics industry...by backing a national flag carrier…; the British attempt to build a computer industry that would rival US firms, based on another national champion, International Computers Limited that never managed to come close to competing with US firms in quality and price; the British Advanced Gas-Cooled Reactor to produce nuclear energy…,which proved to be the wrong line for developing nuclear energy; ...the British Alvey Programme, designed to meet increasing Japanese dominance in computer hardware in the early 1980s, a 'technology push' programme that failed partly because of its 'top-down' bureaucratic structure for administration; Japanese attempt in the 1950s and 1960s to build from scratch a full commercial aircraft industry, which…[failed commercially although creating some technological advances]." (pp 524-5).

In the chapter that follows this quotation the authors study many cases of both successful and unsuccessful industrial policies. Generalising from these, they suggest conditions that tend to favour success rather than failure. Here is a selection of the nearly two dozen conditions that they isolate (pp 534-7): large [technological] leaps are dangerous; pushing the technology off its established trajectory is dangerous; flexibility is important; diversity is one of the best protections against uncertainty; multiple objectives are dangerous; national prestige should be an outcome, not an objective; policies and programmes need independent periodical reviews; market forces and market expertise of private-sector agents should be utilised whenever possible;

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[6] For a full treatment of this instructive case see Womack, Jones, and Roos.

[7] The many successes of the industrial policies of the emerging countries of Southeast Asia are fully documented in O'Neil (Chapter 3) and are discussed in Section 5 of Juhász, Lane and Rodrik.

[8] As documented by O'Neill, South Korea's president Park acted by "…personally choosing winners to lavish with tax breaks, cheap money, loan guarantees, tariff rebates, and even lower electricity and water prices.... Park protected the *choebls* [the nation's traditional conglomerates] from foreign competition, giving them time to learn and grow…. For those that failed to export, licences and access dried up, leading many once-famed businesses and family dynasties to disappear." (p 76).

firms should have a substantial financial stake in any public-sector initiative that involves them; government should avoid picking winners through their own bureaucratic process.

The overall lesson is that, properly and carefully administered by a balanced cooperation between the NPS and the FPS, broadly defined industrial policies can be successful but the dangers are great and the failures numerous.[9]

5. CRITICS OF THE PART PLAYED BY THE NPS IN ASSISTING TECHNOLOGICAL ADVANCE.[10]

It is probably correct that only a few decades ago the majority view of economists held that industrial policy broadly defined mainly produced failures. Today, in contrast, there is a large and growing body of evidence that the three policies listed in the three previous sections have had so many successes that they can no longer be dismissed by such slogans a "Governments cannot pick winners" Here we outline and assess a few of the criticisms that are still repeated in some quarters.

5.1 Who sets the relevant NFP Policies

Many critics tend to imply, without always stating it explicitly, that NPS agents who make decisions about industrial policy and other methods of encouraging technological advance are usually politicians and economically unsophisticated bureaucrats. As Juhász, Lane and Rodrik put one aspect of this criticism (in order to reject it), "...even if the market failures on which governments could act are widespread, real-world governments are unlikely to know enough about the location and magnitude of these failures to make the correct decisions." (p 6)

Listed below is a selection of the NPS organisations that have *directly* contributed to the technological advances in the ten cases studied by Carlaw and Lipsey.[11] Every one of these organisations made a positive NPS-based contribution to the development of one or more of the ten technologies considered by these authors–some just a single contribution, others several contributions in a single area, yet others many contributions covering many areas. This list shows that the critic's assumption concerning who sets and administers industrial policy is unrealistic.[12]

> The UK Admiralty the US Navy, the US Army Airforce, the US Air Mail Act, the US Air Commerce Act, the National Advisory Committee on Aviation (NACA), NASA, the US Department of Defence, the Federal Aviation Authority (FAA), the UK's Brabazon Committee, the French Civil Aircraft Committee, the US Department of Agriculture, the Japanese National Agricultural Experimental Station, the US Bureau of Plant Industry, the International Rice Research Institute (Philippines), the Rockefeller Foundation, The

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[9] The US Build Back Better and Inflation Reduction Acts of 2021 and 2022 have often been billed as modern examples of industrial policies. Indeed, these acts have between them all of the objectives mentioned in Section 1, of which the last, encouraging economic growth, is probably one of the least important. Thus most of their provisions do not fall under the heading of 'growth-inducing industrial policy' and it is beyond the scope of this paper to attempt to assess them.

[10] These criticisms are considered at this point because they do not apply to science policy, a consideration of which is postponed to the next section.

[11] Organisations that contributed to other technologies, or to other fields, such as medicine and architecture, are not included.

[12] With only a few exceptions, the organizations are listed in the order that they appear in the Carlaw and Lipsey monograph.

> Royal Institution and the Royal Society of Great Britain, the Franklin Institute of Philadelphia, the US Rural Electrical Administration, the TVA, the Hydro Electric Commission of Ontario, the Agronomy Department of Iowa State University, the US National Bureau of Standards, the Princeton Institute for Advanced Studies, Bell Labs (although privately owned, 70-80 percent its research has been publicly funded over the years), RAND, the National Science Foundation, the US Advanced Research Projects Agency (ARPA), the NRCS, the Joint Services Electronics Project, the US Office of Naval Research, the US Army's Ballistics Research Laboratory, The US Air Force, the Cambridge Research Centre, the Johns Hopkins Applied Physics Laboratory, the US Army Signal Corps, the P. S. Lebedev Physical Institute operated by the Russian Academy of Sciences, the US Public Health Service, the National Institutes of Health,

5.2 Unproductive Motives

The critics often argue that these NPS agents are typically mainly concerned with political advantages. As Juhász, Lane and Rodrik put this one (again to reject it): "... industrial policy opens the door to self-interested lobbying and political influence activities, diverting the government into activities that enrich private interests without enlarging the social pie." Although it is clear that some examples of industrial policy are reasonably described by this criticism, it does not describe the various motivations of all those agents listed in the previous subsection. Indeed, motivations vary enormously across these organisations, some being concerned directly with the advancement of particular technologies, others with non-economic (e.g., military) objectives for which the technologies they encourage were relevant, others being motivated by pure scientific curiosity, and so on. Those who administer these organisations range over the whole gamut from pure scientists, to applied scientists, to well informed administrators, to accountants, bankers, economists, medical professionals, bureaucrats, many of whom were formally scientists or engineers, and so on.[13]

5.3 Various means

When criticising industrial policy the critics often concrete on the use of subsidies. Although direct subsidies are sometimes used, they are only one of the many instruments for achieving the objectives of technological advance. Some NPS organisations do the research themselves; others finance research done by firms in the FPS with grants, loans and/or favourable purchasing contracts; others provide expert consultancy services; others make innovations that are of general use in some industry; yet others provide centralised information gathering and dissemination as well as sounding boards for new ideas.

5.4 Call for an overall success rate

Even when the critics agree that some NPS efforts were successful, some argue that until we know the *overall success rate*, we have no way of judging how important these efforts have been. Two of the many reasons why this is an impossible demand are that the benefits of some new technology often extend into the indefinite future and that different technologies typically

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[13] The following site lists 21 US Federal government agencies that employ scientists and do R&D. It is beyond the scope of this paper to assess the contributions of each of these, but their presence refutes the myth that technology enhancing policies are mainly administered by politicians and unsophisticated bureaucrats. https://www.google.com/search?q=list+of+government+science+agencies&rlz=1C1SQJL_enCA876CA876&oq=&aqs=chrome.1.35i39i362l3j46i39i175i199i362j35i39i362l2j69i59i450l2.1369668748j0j15&sourceid=chrome&ie=UTF-8, accessed February 2023.

work together to create new technologies. Also the policy interventions are not all monetary ones and neither are many of the results easily measured in monetary terms. Consider for example the US National Advisory Committee on Aeronautics' (NACA) support of invention and innovation in the aircraft industry in the 1920s and 1930s through its government-operated experimental facilities. Among other things, NACA pioneered the development of large wind tunnels; it provided essential test data that led to the development of such innovations as the "NACA cowl"; it demonstrated the superiority of airframes designed with a retractable landing gear. For another example, as Lipsey and Carlaw (1996: p 314) observe "…support for the US semiconductor industry came for many years from military procurement designed to produce innovation.... [T]he military imposed rigid standards and quality control which helped to standardise practises and diffused technological knowledge. [P]rocurement contracts were (and are) awarded by having firms compete to produce a prototype and awarding the best design with a long-term supply contract. This fostered competition in innovation for the contracts and provided a secure market for the successful innovators."

5.5 Could the technologies have been invented by the FPS agents acting alone?

Critics have often argued that even if some efforts were successful, most (all?) of the technological advances would have happened within an acceptable period of time without the assistance from the NPS. This assertion seems impossible to maintain. Here are just a few examples, although the list could be extended over many pages.

With nuclear energy a string of mainly NPS-centred agents, starting late in the 19th century, made discoveries that established the trajectory until the main efforts were transferred to the US government after it entered World War II.[14] Take away the activities of agents acting in the NPS, and the massive NPS funding all before 1960, and it is clear that peaceful atomic energy, if it had ever happened, would have been delayed for decades.

On space exploration Robert Goddard's work was critical in developing early knowledge about rocket propulsion. He was initially self-financed but later received support from the Smithsonian Institute, the National Geographic Society, and the Aero Club of America and the Gugenheim Foundation. The German V2 Rocket used many of Goddard's ideas to become the most advanced rocket system at the time. Later when developed by massive NPS funding a space rocket reached the moon. Rockets made possible satellite technologies which are now the basis of such things as weather forecasting and the GPS, which was itself developed almost exclusively by military funding.

The green revolution was started with funding from the Rockefeller foundation and was later carried on by other NPS sources. It is doubtful when and how many of these developments would have been made solely by the FPS, but certainly the problem of feeding the world's population, particularly in the less developed countries, would have been vastly more serious than it now is.

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[14] E.g., Rontgen, Becquerel, Villard, Pierre and Marie Currie, Prescott, Rutherford, Bohr, Soddy, Chadwick, Cockcroft, Walton, Currie and Joliot, Fermi, Hahn, Strassmann, Meitner and Frisch, Perrin. Important developments occurred in the UK's MAUD Committee. Although sources of funding are seldom mentioned in accounts concerning such people as these, it is clear that most if not all of them were operating in the NPS.

The developments of non-fossil energy sources, including wind, solar, geothermal. and nuclear fission have been to a great extent financed by, and often done in their early stages by, NPS agents.

6. SCIENCE POLICY

Among the many agents of science policies are university and government research labs, such as the National Research Council of Canada, the National Science Foundation, and the National Institutes of Health in the US, along with legislative bodies that make direct grants.

To begin, three key points need to be made about science policy. First, it is by far the most important of the four policies as a basic determinant of long-term economic growth. If science-policy finance coming from all its NPS sources had not been forthcoming, the vast majority of the 20th century's scientific advances would not have occurred. If so, many probably the majority, of the technologies that have transformed people's lives over the last 120 years would not have existed. Second, science policy has received little attention from economic theorists who seldom enquire deeply into the microeconomic sources of the technological advances about which they theorise. Third, the motivations of its agents are not typically directed towards the myriad growth-inducing technological advances that their policies enable; instead, these are largely unintended by products.

In what follows the general relation between developments in science and the First and Second Industrial Revolutions is discussed first. Then the relation between developments in modern science and modern technology are studied in more detail. A full understanding of this relation is important both for our general understanding of the growth process and for evaluating public policy.

6.1 Science and the Industrial Revolutions

There has been debate among economic historians about the importance of science in the development of the technologies of the First Industrial Revolution. The classic contributions that stated the case for the importance of science were by Musson and Robinson and by Schofield. The opposite position was argued in an influential treatment by Landes, followed by White and Rosenberg, among others. Bekar and Lipsey sided with Musson and Robinson with new arguments for the importance of science in the First Industrial Revolution. Although there is insufficient space here to discuss this issue in detail, a few important points need to be made.

The counterargument relies to a great extent on the fact that one cannot point to new scientific discoveries in the 18th and 19th centuries that led directly to new technologies—as did happen in much in the 20th century. In contrast Bekar and Lipsey observed that early modern science, say from 1450 to 1700, did not consist of establishing embracing generalisations but rather it tested, and to a great extent refuted, generalisations that had been accepted since the time of Aristotle. As Margret Jacob argues in her extensive treatment: "The role of science…was not that of general laws leading to the development of specific applications. Instead it…[provided] the theoretical mechanics and the practical mathematics that facilitated technological advance. Brought together by a shared technical vocabulary of Newtonian origin, engineers and entrepreneurs …negotiated…the mechanization of workshops or the improvement of canals, mines, and harbours." (p 115) Indeed she shows that science, as it was then practiced, pervaded the whole structure of British society, from preachers teaching that Newton had revealed the architecture that God had imposed during creation, to a journal teaching Newtonian science to women.

Kenneth Pomeranz has shown that China displayed virtually all of the conditions that Britain had at the beginning of the First Industrial Revolution, leading many to wonder why China did not produce is own industrial revolution. In answer Bekar and Lipsey, point out that one important difference between the two countries was that British society was imbued with Newtonian mechanical science while Chinese society knew nothing of this. (For details of this argument see Lipsey, Carlaw and Bekar Chapter 8, "Why Not Elsewhere?")

Moving to the Second Industrial Revolution at the end of the 19th century, it is more generally accepted that scientific developments did significantly influence technological advance. According to Bekar and Lipsey:

> "…chemicals and steel were two of its [the Second Industrial Revolution's] key products and they both required applications of fairly advanced …science. The industrial laboratory was invented at this time. It was through this institution, along with the new university departments of applied science, that the West invented how to invent. From that time on, science came to play a growing part in technological advance, a part so obvious that it needs no further elaboration..." (p 739)

In this context, it is also important to note that the new FPS industrial laboratories of the early 20th century were concerned with immediate technological applications. These did not typically lead to path-dependent developments of more fundamental scientific knowledge and technological spin-offs–as did the activities of those who were interested in pure scientific knowledge, which are discussed in the next section.

6.2 Modern pure science has been intimately related to technological advance.

Most economic theorists have concentrated on the development of the relevant technologies without considering in any detail their scientific origins. It is contended here that to understand the roots of growth-inducing technological advances one needs to understand these origins. So this sub-section follows Suzzy Sheehy in making up for these omissions. Sheehy's book is built around the development of ten discoveries in pure physics that changed the nature of how scientists understand the physical world. She emphasises the often long and torturous efforts to develop the equipment that allowed these discoveries to be made, as well as the spinoffs to commercially viable applications that these made possible. Sometimes these came from the equipment itself, at least suitably modified, and sometimes from the new technologies that were made possible by the discoveries.

The treatment here abstracts the messages from Sheehy's book that seem appropriate to a concern about how public policy influences the development of new technologies. Except where noted otherwise, all of the factual material in this sub-section comes from Sheehy. Minimal description is given of the development of each of the great discoveries that she studies in detail and that were done almost exclusively by the NPS. Then follows just a selection of the spinoffs to applied technologies that she shows to have come from each discovery. One of the most valuable of her conclusions is the following:

> "These interconnections between fundamental and applied science, industry and discovery are usually separate stories told by scientists and entrepreneurs. We hear the tale of discovery from the physicists and the tale of innovation and commercial success

from the entrepreneurs, but somehow forget about the symbiosis between them." (Sheehy p 212)

The Electron: The discovery of the electron by two NFP agents, Wilhelm Röntgen and Joseph Thompson, upset the current view that the atom was the smallest entity in the physical world. Soon after that, Thomas Edison invented the electronic valve that could stop or start the flow of electrons that constitute electricity. Edison, operating in the FPS, patented it but did nothing further because he could see no immediate commercial value for it. In contrast, John Fleming, operating in the NPS, perceived it's many uses and the electronics industry was born. "It took half a century for electronics and almost a full century for X-rays to realise their current potential…. [T]he fundamental concepts on which these technologies were based came from inquisitive minds performing experiments in an effort to increase our collective knowledge." (Sheehy p 27)

The Atom and radiation: Ernest Rutherford, and Frederick Saudi, both operating in the NPS, discovered the true nature of the atom to be not a solid but a small central core circulated by distant electrons. That discovery, plus their understanding of the nature of radiation as caused by the spontaneous decay of atoms, led to many practical results, including the radiometric dating of materials. "The quest to understand the smallest objects in nature might have seemed like an obscure bit of physics at the time, but it has come to underpin much of our understanding of culture, art, geology, and our place in world history." (Sheehy p 44)

The Photoelectric Effect: The explanation of the photo electric effect, that a beam of light can knock electrons off a metal shield, led to the discovery that light was both a wave and a particle that had a fixed *quantum* of mass and energy. With this discovery, quantum electrodynamics was begun. "The properties of semiconductor materials combined with the physics of the photoelectric effect enabled development of a vast array of electrical components…" (Sheehy p 58) These include cells that turn sunlight into electric energy, satellite communications, proximity sensors that open doors, and laser-based measurements. "Our future technologies are likely to be almost entirely based in quantum mechanics." (Sheehy p 66)

The Positron: A revolutionary discovery in the early 20th century using the newly developed cloud chamber, was the positron, a particle identical to the electron except that it has the opposite charge. It also led to the discovery of short-lived particles, muons, that have the important property of going straight through most matter and so not scattering as do electrons and X-rays. This vastly increased the discerning power of scanners. Muons are now used to image a vast array of things such as container ships and power stations, dense mineral deposits, caves, and tunnels.

The First Particle Accelerators: The first successful particle accelerator was developed in 1932 and ended the long search to discover the nature of the atomic core. Scientifically this began the subject of nuclear physics but it also had many practical applications including carbon dating of materials. Also to "…make a semiconductor like silicon into a useful [device] it needs to be made slightly impure by adding dopants: tiny amounts of other elements…. The only precise way to do this is to control individual ions and implant them using a particle accelerator." (Sheehy p 116) Semiconductors are now used in a wide range of consumer products such a TVs, cameras, and washing machines.

The Cyclotron: The cyclotron achieved energies sufficient to smash any atom, which earlier accelerators could not do. The practical applications were mainly clinical. Cyclotrons are used today to treat diseases and diagnose the malfunctioning of organs.

Bevatrons and cosmotrons: These can accelerate electrons which the earlier accelerators could not.[15] An accidental discovery during the development of the Betatron was that the stream of electrons that it produced was an emission now called synchrotron radiation. "It can be incredibly intense, it's coherent (laser-like rather than light-bulb-like) and it can cover the full electromagnetic spectrum, from X-ray through visible light to infrared, depending on the magnetic field and the electron energy. The light is also *polarised*…." (Sheehy p 146). It turned out to be superior to any other light source or X-ray. " …by 1970 the first user facility was built: [with NSF funding]: the Synchrotron Radiation Source (SRS) at Daresbury Laboratory in the UK. Governments around the world started building particle accelerators to meet the demands of a vast range of scientific and commercial users." (Sheehy p 148).

Many facilities similar to those at Daresbury were built by governments around the world. Much later when the Daresbury facility was eventually shut down in 2008, a study "…identified thousands of discoveries that have affected our lives in direct and indirect ways. New materials for clothing and electronics, new pharmaceuticals and new detergents are just a few of the products that emerged from the studies at this one facility." (Sheehy p 153)

When Bevatrons replaced X-rays in crystallography they were vastly more powerful, which was a great advantage when the need came to quickly discover the structure of the virus that caused COVID. Also it was soon realised that beams of heavy charged particles could be more suitable in treating cancers deep inside the body than previously used technologies. "Today, more than a hundred centres around the world offer *particle-therapy* which is particularly well suited to deep and hard-to-reach tumours, difficult childhood cases, or tumours near critical organs." (Sheehy p 177)

The Neutrino: Neutrinos are one of the most abundant particles in the universe but being without electrical charge and almost massless and weightless, they were hard to detect and finding them was a triumph of measurement. "Neutrinos didn't just help us understand radioactive decay; they have led us to a new view of the Sun, supernovae and the origin of matter." (Sheehy p 189) Unlike every advance considered so far, the neutrino has not yet been shown to have practical applications in the development of new technologies. But there are some suggestions. They "… may indirectly help us transition from fossil fuels and nuclear fission reactors as a source of power to *fusion* reactors…but getting one working requires that we are absolutely confident in our knowledge of nuclear physics. This knowledge has come in part from

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[15] Virtually all the scientific developments discussed so far were made by agents in the NPS (while many of the applications that were based on these developments were made in the FPS). In the case of Betatrons, however, a significant part of the scientific work was done by the Bell labs, which as Carlaw and Lipsey point out inhabit some middling position straddling the two sectors. "Initially, Bell Labs was entirely funded by AT&T and its entities. During World War II, however, Bell Laboratories received more than two thousand military contracts, support that did not cease when the war ended. Between 1949 and 1959, about half of the Lab's research budget came from the US government..." (Carlaw and Lipsey pp 80-1). Also, the first team that built a working betatron was based at the NPS University of Illinois.

solar neutrino experiments... which have confirmed that our model of how neutrinos are formed in the sun is correct." (Sheehy p 196)

Quarks: The discoveries discussed in this sub-section show an interesting path dependency: "The quark discovery was enabled by the linear accelerator, which itself required cyclotrons and magnetrons, which in turn had been created to provide high-power radar technology." (Sheehy p 212) First in this sequence came radar. Then came linear accelerators followed by the magnetron and the klystron, that produced high-frequency pulses of a much shorter wavelengths than the then-existing radar systems. When it was discovered accidentally that these devices produced heat, the microwave oven was invented. Today, these devices are used to transmit 600,000 conversations simultaneously while its beams guide aircraft along safe flight paths. Smaller and more compact versions of linear accelerators are used today in hospitals to treat cancer successfully. Other smaller accelerators have many uses, such as in security scanner systems and treating water waste from factories without using harsh chemicals. Later Fermilab built the even more powerful Tevatron, overcoming enormous technical problems. This was eventually used to discover the last quark to be found, the top quark, heaviest of all the quarks. One of the most important spinoffs from the Tevatron was the now commonly used and enormously valuable MRI. This uses the type of superconducting magnets that were invented as part of the development of the Tevatron. Superconducting magnets are also used to levitate those trains that no longer run on tracks, as well as in experimental fusion reactors and energy storage systems.

The Higgs Boson: The last element of the standard model to be discovered was the force-carrying particle, the Higgs boson. The only facility able to create enough energy to search effectively for such a particle was the Large Hadron Collider (LHC) at CERN, Switzerland. A vast number of mainly NPS researchers distributed throughout the world were required for the development and operation of the LHC. To coordinate these activities, Tim Berners-Lee invented what became the World Wide Web–a life-changing spinoff from this scientific research. Some of the many other technological spinoffs are "… collaborative software systems, radiation-hard detectors used in medicine, and compact orbital cutters to cut huge pieces of pipe in the field. The unique requirements of CERN'S large experiments have continually pushed industry to innovate in order to supply state-of-the-art components. In a survey, 75 percent of suppliers to CERN noted they had increased their capacity to innovate through contracting with CERN." (Sheehy p 258).

7. CONCLUSION AND POLICY IMPLIATIONS

Many investigators who have recently studied the contributions of both the NPS and the FPS to growth-inducing technological advance have concluded that agents in both sectors have made significant contributions. As Mazzucato puts it after an extensive study of the evidence:

> "In countries that owe their growth to innovation–and in regions within those countries, like Silicon Valley–the state has historically served not just as an administrator and regulator of the wealth creation process, but a key actor in it, and often the more daring one, willing to take the risks that businesses won't. This has been true not only in the narrow areas that economists call 'public goods' (like funding of basic research) but across the entire innovation chain, from basic research to applied research, commercialization and early-stage financing of companies themselves." (p 4)

Most theorists of economic growth have ignored the NPS. But no economists and economic historians who have studied the two sectors in any detail have provided evidence that the contributions of the NPS were insignificant. Agents in the NPS who have been important include the research sections of many government departments, many agencies established and financed by governments, many independent NGOs and many individuals not concerned with monetary gains. The evidence tells us what has happened. The counterfactual of what might have happened if these NPS interventions had not occurred requires imagining a totally different world.

Technology, R&D, and industrial policies can be used for purposes other than encouraging economic growth, such as greening the economy and reducing imports of some sensitive commodities for political or military reasons. But the subject of this paper is policies that encourage growth-inducing technological advance.

Of the four such policies studied here, technology policy is the most direct, targeting the technologies themselves. R&D policy is a bit less direct, targeting either R&D in general or R&D directed at a certain range of inventions and/or innovations. Growth-inducing industrial policy is further removed by targeting particular firms and industries in the hope that they will innovate new technologies. Science policy seems the most removed of the four. But things are not quite so simple. Growth-inducing industrial policy relies on firms perceiving opportunities for technological advance, many of which were not created by their own research. In contrast, science policy creates, even if indirectly, myriad opportunities for technological advance. Technology policy can then encourage firms to exploit these developments without requiring any direct industrial policy, which is after all a policy whose history contains many failures as well as many successes.

If asked to give advice on how to encourage economic growth in the already-developed countries, as well as the obvious background institutional and education conditions, I would recommend a heavy investment in science policy for its indirect spinoffs, and in technology and R&D policies to assist firms in innovating on the basis of these newly created opportunities. If public funds are available to assist in the early development of the new technologies, there is no need to directly assist particular firms through a growth-inducing industrial policy. Instead firms can be left to compete for the opportunity to do so. If this advice seems novel, it is because few if any growth theorists have listed science policy as a major cause of economic growth or suggested encouraging it as a means of influencing such growth.

There is a possible problem here since scientific discoveries quickly become public knowledge. This may make it seem attractive for a country to freeload on other country's financing of scientific discoveries and then take advantage of the spinoffs without the initial cost of making the original discoveries. This is something that the developing countries that are not at the technological frontier must do. But things are different for the developed countries. Science is required not just for discovering things of interest to pure science, but also in the early and sometimes even the later stages of the developments and applications of these spinoffs. For this reason, countries that invest heavily in scientific discoveries may also have much of the human capital that is suited to exploit the technological spinoffs.

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