INDUSTRIAL POLICIES: Common Not Rare

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ABSTRACT

This paper reviews some of the myriad, often complex, ways in which the private and public sectors interact in the invention and innovation of the new technologies that are a major driver of economic growth. Several terms have been used to describe the public sector's activities in these matters: technology enhancement policy, innovation policy, industrial policy, and national systems of innovation. We use the term *Industrial Policies* to cover all the public sector's activities that, either directly or indirectly, encourage technological advance. We first outline some important concepts and definitions: two views of the place of the public sector in technological advance; the definition of technology and the facilitating structure; the main public sector organisations that encourage technological advance; the four evolutionary trajectories of a new technology: invention, efficiency, applications and diffusion; the growing importance of science in technological advance; and an overview of a successful industrial policy. In Section II we study 13 important technologies developed over the last century and a half, showing the extent that the public sector has provided finance for the various trajectories of these technologies. In Section III we consider nine public policies designed to encourage technological advance in general. Then in section IV, we discuss over 20 cases in which the government has attempted to pick and encourage specific winners, some of which were successes while others were failures. After each of our case studies in our three main sections, we offer at least one tentative lesson concerning the conditions that favour success and/or that tend to lead to failure. Section V offers a few concluding remarks ending with the statement that "The cases considered here reveal that those who would dismiss industrial policy with statements such as 'Governments cannot pick winners' are relying on an empty slogan to avoid detailed consideration of the actual complicated, multifaceted relationship between the private and public sectors in encouraging the inventions and innovations that are the root of economic growth.

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INDUSTRIAL POLICIES: Endemic not Epidemic

"All nations have their myths. The trouble with Americans is that they believe their own [free market] myths."
A senior Canadian federal civil servant in conversation with RGL.

The vast range of policies loosely grouped under the heading 'industrial policies' has a long and varied history, being both lauded by many and condemned by others. An assessment of these policies is particularly important today for at least two reasons. First, many of those who accept the seriousness of human-created climate change advocate the use of various forms of industrial policy, both to slow these changes and to mitigate some of their effects. Second, in the US the Trump administration has attacked the science base of many government departments thereby dismantling what many regard as a necessary part of what they see as one of the world's most successful systems of industrial policies: the cooperation between the American public and the private sectors in the process of invention and innovation.

Several terms have been used to describe some or all the matters that will be considered here: technology enhancement policy, innovation policy, industrial policy, and national systems of innovation. Our concern here is with the relative influences on economic growth of what we call, as a first approximation, the economy's private and public sectors. (See a later section for important elaborations.) Since we need some term, we hereafter use *Industrial Policies* but understand these in the wide context that is described below.

Our first step is briefly to outline two basic views that underly different assessments of the relative growth-inducing potential of the private and public sectors. Then, after a consideration of some important concepts and definitions, we present three main sections. The first shows how some important technologies have been financed by both the public and the private sectors. The second considers some public sector measures designed to encourage inventions and innovations in a general way, not focussed on a particular product or firm. The third considers some attempts to encourage the development of a particular product and/or firm, commonly known as 'picking winners', as well as some lessons that can be learned from both the successes and the failures of these attempts. We make no attempt to cover all possible cases in each of these three sections but rather to consider enough examples to establish the main points that we wish to make in each section about the nature and pervasiveness of industrial policies.

I. SOME IMPORTANT CONCEPTS AND DEFINITIONS[1]

At the outset we need to outline some important concepts and define some important terms, many of which are borrowed from Lipsey, Carlaw and Bekar (2005), hereafter LCB.

Policy Implications of Two Views of the Economy

The so-called neoclassical view holds that the place of government in the economy is to provide a level playing field and remove market imperfections, leaving the private sector to generate an efficient allocation of resources and an optimum amount of economic growth. An important market imperfection pointed out by Kenneth Arrow (1962) lies in the large (net positive) externalities associated with the introduction of new products and processes that result in a sub-optimal amount of R&D for the whole economy. This provides a reason for the government to subsidise R&D to ensure that the aggregate amount gets closer to the social optimum. Assuming that the decision environment is characterised by risk rather than uncertainty, the private sector can then be relied on to equate the expected marginal products of all lines of R&D so that there is no justification for anything other than a generalised, and hence 'non-distorting', R&D subsidy. We should note in passing that this view was upset long ago by the General Theory of Second Best (Lipsey and Lancaster 1958), which shows that if all market imperfections cannot be removed or compensated for, there is no presumption that removing any one will raise the value of whatever objective function is being considered–usually some index of community welfare.

One intellectual basis for supporting public sector activities that go beyond what is sanctioned in the neoclassical view is in what Carlaw and Lipsey (1998) call the 'structuralist evolutionary' (S-E) view of the economy.[2] Without going into detail here, this view emphasises two important aspects of the real economy: (i) pervasive uncertainty and (ii) the endogeneity of both technological change[3] and, at least to some extent, scientific research.[4] The fact that invention and innovation are fraught with uncertainties upsets the idea that the private sector will allocate resources, including R&D, in a socially optimal way. (In fact, the existence of uncertainty precludes the possibility of articulating a social optimum, and so resource allocations cannot be assessed according to such criteria.) Large sums must often be invested before it can be known whether a particular line of research

[1] The first five parts of this section are based on Carlaw and Lipsey (forthcoming).

[2] This is described in more detail in Lipsey and Carlaw (1998).

[3] Popularised by Joseph Schumpeter and documented by many economic historians long before it was introduced into macro models by Romer and Lucas.

[4] Argued persuasively by Rosenberg (1982: Chapter 7).

will yield enormous, modest or negative profits. Thus, rather than maximising the expected value of profits from all lines of activity, firms should be seen as groping into an uncertain future in a profit-oriented but not profit-maximising matter. The fact that technological change is endogenous (being influenced by actions in both the private and public sectors), undermines the view, that the socially optimal policy is to allocate resources efficiently *given the current state of technology*−as was pointed out long ago by the Scottish born, Canadian economist, John Rae (1905).

In summary, neoclassical policy advice is simple and general (as long as we ignore second best, and the existence of pervasive uncertainty), applying to all countries: remove market imperfections wherever they are found. In contrast, S-E advice is context dependent, there being no simple set of policy rules that apply to all countries, all times, and all circumstances (which is true both in the SE and the neoclassical, second-best worlds). Instead of removing market imperfections, which can only be defined in relation to imaginary (or assumed) optimal criteria, the S-E advice is to formulate policy interventions on the basis of informed judgements that seek to achieve improved outcomes relative to current circumstances.

Technology and Structure

LCB (2005: 58) define *technological knowledge, technology for short*, as "…the set of ideas specifying all activities that create economic value. It covers product, process, and organizational technologies". The concept distinguishes technology from its physical embodiment in capital goods and leads to the following definition. *The facilitating structure* (as defined by LCB, 2005: 60-1) is the set of realisations of technological knowledge, i.e., "the actual physical objects, people, structures and organisational forms, in which technological knowledge is embodied".[5] Major new technologies often cause large and persistent changes in the facilitating structure.

Agents

Carlaw and Lipsey (forthcoming) divide agents into two major groups the for-profit sector (FPS) and the not-for-profit sector (NPS). They then subdivide the

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[5] The structure includes (1) all physical capital, (2) consumers' durables and residential housing, (3) people: who they are, where they live, and all human capital that resides in them and that is related to productive activities, including tacit knowledge of how to operate existing value-creating facilities, (4) the actual physical organisation of production facilities, including labour practices, (5 the managerial and financial organisation of firms, (6) the geographical location of productive activities, (7) industrial concentration, (8) all infrastructure, (9) all private-sector financial institutions, and financial instruments, (10) government owned industries, (11) educational institutions, (12) all research units whether in the public or the private sector (LCB, 2005: 60-1).

NPS into several subgroups. Although we do not use many of these distinctions in this paper, we note them all here because it is one of the many ways in which industrial policy is more complex than is apparent from much of the popular discussion. The NPS is divided into two groups, non-government organisations (NGOs) and the public policy sector (PPS) and the PPS sector is in turn subdivided into two groups, those that primarily seek economic objectives (EOs) and those that seek other objectives (NEOs). In summary:

FIGURE 1 FINANCING SECTORS

- FPS
- NPS
  - NGO
  - PPS
    - EO
    - NEO

The for-profit sector includes individuals and organisations operating in pursuit of market incentives such as profits, sales, management earnings, or other similar economic objectives, which we call collectively *economic returns*. These are the agents that inhabit any standard textbook on micro economic theory.

The not-for-profit sector includes all other agents, but we confine our attention to those whose activities, either directly or indirectly, affect the evolution of technologies in any of their trajectories outlined below. Sometimes we treat this sector as a whole but at other times it is useful to consider its subdivisions.

The non-government organisation sector (NGO) includes both non-government organisations and individuals whose activities are not motivated by a search for profits, but by such non-monetary incentives as pure curiosity, philanthropy, the pursuit of knowledge, and personal prestige. Their activities, however, create opportunities (and influence evolutionary trajectories) either directly or indirectly, in some cases allowing others to make economic returns.[6]

[6] It is not always clear if the activities of a self-financed individual agent fall within the NGOS or the FPS. Fortunately, when the agent was financed by an outside body, it is usually possible to tell if the financing came from either the FPS or the NPS, which is our main concern.

The public policy sector (*PPS*)[7] This second sub-category of the NPS can itself be subdivided into two groups distinguished by motivations. The EOS includes publicly funded organisations that implement policies in pursuit of economic objectives either directly through scientific and/or technological advance or indirectly, as when the facilitating structure is altered by such means as building roads or contributing to the health and education of workers. Others in the PPS are concerned with achieving non-economic objectives that will benefit themselves, such as military power or election victories (NEO). Their activities in pursuit of these objectives often have important technological spin offs.

There is an important ambiguity concerning where the boundary lies *within* one major actor, e.g., Bell Laboratories, rather than with the general boundary between any of our main sectors. Although at its inception Bell Labs' work was mainly financed by AT&T, and hence the FPS, the research became increasingly dependent on government financing during and after World War II, and hence the NPS. It is possible to locate specific funding grants from outside Bell Labs in some cases but not others. In the latter cases it is unclear whether the financing was NPS or FPS, although often it was both.

Evolutionary Trajectories

We need to distinguish four trajectories that are distinct in principle but often are so intertwined that they cannot be dealt with separately in practice. Policies differ in the trajectory that they seek to influence.

The *invention trajectory* begins with all the scientific and technological developments that precede the emergence of an identifiable, workable technology. Since new technological knowledge evolves continually, it is somewhat arbitrary to state exactly when the invention stage is over. It may roughly be thought of as ending when 'proof of concept' is established.

The *efficiency trajectory* is the time path of the cost of producing a unit of the service provided by the technology. When more than one service is provided it is an index of the multi-dimensional array of the costs of these various services.

The *applications trajectory* is composed of the technological products, processes, and forms of organization that depend on it (as the electric washing

[7] The boundary between the NGOS and the PPS is neither clear nor invariant over time. Although we are interested in distinguishing the financing that come from these two groups, it is the clearer division between the FPS and the NPS financing that is most important to us.

machine depends on electricity), or include it, in one form or another (as when a robot incorporates a computer).

The *diffusion trajectory* is the spread of the technology to uses in other places, as when computers spread from the scientific lab to the office and from the countries where it was invented to the rest of the world.

Several points need to be noted about these trajectories.

First, diffusion is often associated with major new applications (e.g., Computers and the Internet, or Lasers and Barcoding for scanning). Because this trajectory is so intimately related to the applications trajectory, we treat these two trajectories together as the diffusion-applications-diffusion trajectory in what follows.

Second, the evolution of the invention, the efficiency and the applications-diffusion trajectories can sometimes be divided into a *pre-commercial stage,* when developments are public property and a *commercial* stage, when development can be appropriated privately.

Third, where the various trajectories are distinct and follow different paths, the failure to distinguish among them has been the cause of much confusion in the literature concerning the evolution of, and the FPS and NPS support for, new technologies.

Science and Technology

There has been a long debate among economic historians about the importance of science in technological developments up to the end of the 19th century. We do not need to go into this debate here except to observe that Lipsey and Becker (2004) and LCB (2005) have argued that science was much more important over that time period than many economic historians have been prepared to admit. Some illustrations of this view are given in the case studies that follow.

What is indisputable is that the place of science in technological advance changed dramatically in the transition from the first industrial revolution, which was based mainly on Newtonian mechanics, and the second industrial revolution, which was based much more firmly in modern science. One of the first R&D labs was Thomas Edison's Menlo Park, which was followed by many other labs in both the private and public sectors. From that time on, science has played an increasingly important part in the development of technologies. This has created a place for publicly financed research where the private sector would not provide the necessary finance due to such things as a lack of adequate financial incentives, insufficient foresight, and an expected very long invention phase. The part played by the public sector has grown steadily as new technologies have become increasingly complex and science based.

Successful Industrial Policies in Action.

Industrial policies are often thought of as top-down attempts by bureaucrats to dictate the path of technological change in the small or even in the large. Indeed, there are cases where this has happened, usually with predictably unfortunate results. We consider some of these in a later section. But there are also what evidence suggests are successful industrial policies. A key characteristic of most of the successful ones is that public and private sector agents engage in cooperative ventures with each concentrating on the areas of their comparative advantage. Considering this view Mariana Mazzucato observes (2015: 4-5, Italics added):

> "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 as a key actor in it, and often a more daring one, willing to take the risks that businesses won't. [In many of these cases] governments envision a *direction* for technological change and invest in that direction. Creating markets not only fixing them. Different from narrow attempts to identify and pick winners, envisaging a direction for economic development and technological change broadens the technological opportunity landscape and requires that the state creates a network of willing (not necessarily 'winning') agents that are keen to seize the opportunity through *public-private partnerships."*

It is important to distinguish between two generic types of industrial policies in pursuit of technological change and economic growth. The first seeks to do so by directly encouraging scientific and/or technological advance. The second operates indirectly by altering the facilitating structure through such means as building roads or contributing to the health and education of workers.

II. THE FINANCING OF SOME MAJOR TECHNOLOGIES.[8]

Carlaw and Lipsey (forthcoming) study the financing of the technologies that are embodied in eleven major products introduced over the last century and a half. Although these studies are mostly qualitative, they throw considerable light on the significant role played by the NPS in financing many major technological developments. Indeed, these cases challenge the view, commonly found, or at least

[8] The material in this section, down to the end of the sub-section on lasers, is a severe abbreviation of material in Carlaw and Lipsey (forthcoming) that covers each of these case studies in much more detail than is presented here. Citations for all the factual evidence presented here are given there but are omitted here in the interests of space.

implied, in economic theory textbooks, that the FPS is the only major force behind the economic evolution that has continually transformed economies over the last nearly 300 years. Figure 2 shows these cases, grouping them according to which of the trajectories outlined above received significant NPS support.

What follows for all these cases is a very brief mention designed to illustrate the extent of NPS funding. A much fuller coverage of each case is set out in Carlaw and Lipsey (forthcoming).

FIGURE 2: SIGNIFICANT DIRECT NOT FOR PROFIT (NPS) ASSISTANCE[9]

	Invention/innovation	Efficiency trajectory	Applications-diffusion-trajectory
GROUP I			
Internal combustion engine			
GROUP II			
Refrigeration	Yes		
GROUP III			
Railways		Yes	Yes
Automobiles		Yes	Yes
Aircraft		Yes	Yes
Agriculture		Yes	Yes
GROUP IV			
Iron steam ships	Yes	Yes	
GROUP V			
Electricity	Yes	Yes	Yes

[9] This is a slightly edited version of the figure in Carlaw and Lipsey (forthcoming).

Computers	Yes	Yes	Yes
Internet	Yes	Yes	Yes
Lasers Apple Products Wind Power	Yes Yes Yes	Yes Yes Yes	Yes Yes Yes

The internal combustion engine

The main reasons why this technology required virtually no NPS support for its invention, efficiency and applications-diffusion trajectories were first, that the technological knowledge required for its invention was well known and second, its potential applications to other technologies were obvious and, in most cases, so was their commercial viability. Nonetheless, the technology's full development required applications in other areas such as motor vehicles, railroads, ships, and aircraft, all of which enjoyed significant NPS support in various forms (see below)

Lesson

- Although the invention, efficiency and direct applications-diffusion trajectories of a new technology may be obvious and commercially viable from the outset, the full development of the efficiency and applications-diffusion trajectories may require the development of other technologies that incorporate the original one. If these, in turn, require NPS finance, this may be indirectly needed for the full development of the initial technology.

Refrigeration

There was serious uncertainty in the invention trajectory of the technology of refrigeration. As a result, certain practical components of it had to be demonstrated before agents in the FPS could foresee opportunities for profitable investments in the technology. As a result, NPS support was needed early in the invention trajectory. This came initially from individuals, many of whom were university professors in the NPS, while others financed their activities with their own funds. Cullen, Franklin and Hadley were almost certainly driven by scientific curiosity. But later contributors, especially those who patented their ideas, were probably driven by a mixture of curiosity and the search for commercial success.

Lessons

- When there is much uncertainty about the technology early on, as it was with refrigeration, certain practical components of it need to be demonstrated before agents in the FPS can foresee profitable investments in the technology. So NPS support and financing is needed early in the invention trajectory.
- If, as with refrigeration, there are many obvious commercial applications once the basic principles have been proven, the trajectories of invention, efficiency, and applications-diffusion can be readily financed by the FPS.

Railroads

For the most part, railroads were initially invented and developed by the FPS in the UK. Agents built where profitable opportunities were obvious. But once proven privately, railroads were supported in their broader development to exploit social returns in several efficiency and applications-diffusion trajectories via PPS support. Carlaw and Lipsey (forthcoming) give numerous examples.

The PPS provided much support for the development of railways in the US, Canada, Australia and Japan. In the first three of these cases, this had much to do with lack of apparent commercial viability due to the large geographic area and the relatively low population density dispersed across the expansive geography combined with the belief. In all four cases, there were large social and economic externalities associated with railways that could not be captured by the FPS owners. Among other things, the US railways turned many regional markets into one national market allowing the exploitation of latent scale economies that did much to create the US dominance in 20th century manufacturing.

Lesson

- Many major new technologies often have massive technological complementarities that manifest as externalities and broader spillovers, which cannot create profits for those who invest in the initial technology and that give reason for considerable PPS support. This support may seem unprofitable on narrow financial calculations but be socially profitable when the externalities are accounted for.

Automobiles

Automobiles are unique in two ways. First, there was little or no support for any of our four trajectories but there was major PPS support for creating the infrastructure that allowed automobiles to flourish, particularly in North America. Second, the Japanese and South Korean post World War II automobile industries were major triumphs of PPS support in picking winners. We consider these two cases in a subsequent section and in much more detail in Carlaw and Lipsey (forthcoming).

Most automobile companies in North America and Europe were started by men who had previously manufactured bicycles or carriages which provided them with the relevant technical knowledge that was embedded in the facilitating structure. There were over one hundred individual manufacturers between 1899 and 1916, all of them FPS funded.

Almost all of the efficiency and applications-diffusion developments were also FPS funded, its commercial applications being obvious once the requisite technology of the internal combustion engine was proven. There are a few exceptions. For example, state support for some European motor companies began before 1914, with subsidies on various types of commercial vehicles suitable for military purposes. For another example, Henry Leland who formed the Lincoln Motor Co. 1917 produced Liberty engines on a cost-plus basis for the military.

By far the most important PPS support came, however, in the form of road infrastructure in both Europe and the North America. Without this support, the motorised vehicle would not have had many of its most important applications in transporting goods and passengers commercially, in reinforcing the growth of city suburbs that had begun with the suburban railway services, in facilitating the growth of suburban shopping centres and in allowing the full development of the tourist industry−all of which encouraged the further development and improvement of motor vehicles.

Lesson

- Many technologies that can be mainly developed by the FPS can only reach their full range and depth of usage without that infrastructure that is to a great extend NPS financed.

Aircraft

In the US, FPS financing came first, followed later by significant PPS support. The private sector proved the viability of early aircraft up to 1914 while the technology was greatly improved by the WW I military (the NEO) and only then was significant PPS support given for commercial aircraft. This is a case of supporting an already obvious winner rather than attempting to create a new one. From the 1920s to the 1950s the National Advisory Committee on Aeronautics (NACA) shaped early American technology policies to assist the commercial aircraft industry. Among its many other activities, importantly:

- it pioneered the construction and use of large wind tunnels that

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 and the cantilevered wings used in many aircraft in the 1930s, including the famous workhorse the DC3.

Between the 1930s and the 1990's the US government regularly funded more than 75% of R&D in the American aircraft industry, most notably, during the 1950s and 1960s when nearly 80% of industry sales were to the government.

The jet engine was developed in both UK and Germany by private individuals and only when these individuals had proven its worth did the reluctant military take them up and develop them during World War II, after which they eventually supplanted all other engine types on almost all but short-range passenger aircraft.

Lesson

- The uncertainty associated with PPS support of a new technology can be greatly reduced if the FPS has already proven that the technology is workable but that there is a long future to its efficiency and application-diffusion trajectories, some of which developments are in the nature of public goods much of whose value cannot be appropriated by the original developer.

Agriculture

Here are a few selected examples of the extensive support by the NPS in a variety of technology developments in agriculture.

  - In 1874 at the request of Dutch tea planters, the Dutch government recommended changes to the planting strategy which improved crop productivity.
  - In 1893 wheat breeding was started at the Japanese National Agricultural Experimental Station. By 1995 there were 143 varieties in total registered and there were seven PPS funded agricultural experimental stations.
  - In 1899 the US Department of Agriculture engaged in rice and crop field experiments.
  - In 1907 Pima cotton was developed by the US Bureau of Plant Industry.

- Between 1960 and 1969 the International Rice Research Institute (IRRI) in the Philippines developed a dwarf semi-tropical rice named IR8.
- In 1962 a research collaboration between Mexico and Canada succeeded in developing two semi-dwarf wheat varieties and in 1966 another robust variety.
- Agricultural research institutes directly supported by the PPS include the US Land Grant Colleges that began in 1862, the Pima Research Station in 1907, the UK's Rowett Research Institute, in 1922 and the Netherland's Agricultural College.
- There are several international NPS supported institutions directly involved in agricultural research, including the IRRI founded in 1960 as a joint effort between the University of Philippines, the Ford Foundation and the Rockefeller Foundation which was played a key part in the Green Revolution.
- Between the 1940s and the late 1970s the Green Revolution that was primarily PPS funded, but also enjoyed significant NGO support. increased agriculture production worldwide. The innovations involved the development of irrigation infrastructure, high-yielding and disease-resistant varieties of cereal grains, and the application of hybridized seeds, synthetic fertilizers, and pesticides. They achieved much higher crop yields for many of the developing economies where they were implemented, but with some unfortunate side effects.

Lesson

- Many of the gains in agricultural productivity in terms of new products and new production processes would never have been undertaken by the FPS because, among other reasons, they were public goods from the outset and they required very long gestation periods before becoming productive.

The Iron Steam Ship

Once high-pressure steam engines had been developed in the early years of the 19th century, these engines entered marine use. Early ships were of wooden construction and powered by paddle wheels. There was initial resistance to iron hulls, particularly from the Royal Navy. But iron was proved superior in 1839 when a storm drove an iron steamer ashore along with several wooden boats. All the wooden boats were destroyed while the iron vessel was undamaged. In 1835, two British inventors patented the first practical screw propellers. The admiralty was again sceptical, maintaining that the propeller would be impractical in heavy weather. But, when a small, privately owned, screw-driven ship was seen to perform well in heavy weather, the Admiralty helped fund the building of the wooden-hulled screw driven *Archimedes.* The shift from paddle wheels to screw propellers required several minor but important inventions. These were required for a reciprocating steam engine to provide a direct drive to a fore-and-aft shaft connected to an external propeller. (We are still researching the sources of the funding for these developments, but they appear to have been a combination of FPS and NPS support.)

Other PPS support for the building and development of ships in the form of schools, professional societies, publication of theoretical works, and experimental research, came soon. The Royal Navy also provided numerous postal subsidies and naval subventions that helped to finance the construction of passenger liners and freighters.

In the US the *City of Peking*, which was an iron hulled, screw driven, steam and sail powered passenger and freight ship was built by the FPS but with a $500,000.00 PPS-subsidy from the US Congress. This is one example of a number of ships built in the US and Britain with some form of PPS support to compete in Transatlantic and Far East trade routes.

General Lesson from the above case studies

- The FPS and NPS often operate together to influence evolutionary trajectories. The relationship is ***not*** unidirectional. The technologies in Groups II and IV, refrigeration and the iron steam ship, and the jet engine in Group III, needed some minimal NPS support to be proven viable in their invention trajectories before their widespread uptake and exploitation by the military (NEO) and then by the FPS. In contrast, most of the technologies in Group III railways, automobiles, and aircraft required the FPS support in the invention trajectory prior to obtaining NPS support for their efficiency and applications-diffusion trajectories.

Electricity

The development of commercially usable electricity in the 19th century is often cited as a development typical of that century when the NPS was assumed to have had little influence on technological change, but what are the facts?

The early development of electricity was almost exclusively financed by NGO and PPS support.

- William Gilbert (physician to the English Crown in the early 17th century) turned a body of empirical observations on the behaviour of the compass needle into a genuine theory of magnetism by his demonstration that the earth was a giant lodestone with its north pole centered near the geographical north pole but significantly below the surface.
- Otto von Guericke (a university-trained scientist and politician) invented a machine to produce an electric charge.
- Du Fay (a member of the French Academy of Science) showed the difference between positive and negative electric charges.
- Benjamin Franklin (Fellow of the Royal Society) showed that atmospheric electricity was identical in form to the charge produced by a Leyden jar.
- Priestly (Fellow of the Royal Society) proved that the force between electric charges varies inversely with the distance between the charges.
- De Coulomb (French Military Engineer and Physicist) subsequently invented an instrument to measure electric charges accurately.
- In 1800, Volta (Professor of physics) produced an electric battery, the Voltaic Pile, which for the first time had obvious commercial applications.
- The early development of more efficient batteries enjoyed a great deal of NGO support. Those involved were mainly professors at European universities or members of institutions such as the NGO funded Royal Institution of Great Britain (which at one time housed Faraday's research laboratory).
- Volta enjoyed NGO funding in several forms. For example, he received the Royal Society's Copley Medal, which came with a sizeable financial prize. Within a year of Volta's letter to the Royal Society describing his pile, members of the Royal Society began experimenting on and building their own stronger batteries, mainly in the interest of advancing scientific knowledge rather than for commercial use.
- The Royal Institution funded experiments, was host to lecturers, and employed a number of scientists working on the development of electricity, most notably Davy and Faraday.
- To overcome the deficiencies of the weak patent system of the day that made manufacturers reluctant to share their processes with the public, the Institution facilitated the sharing of knowledge by building

one of the best-equipped labs in Europe and inviting key players to do research there.

- NGO support was also provided by the Royal Society which supported many of the breakthrough inventions related to the battery. It also rewarded inventors with financial prizes.
- PPS funding for the development of the battery included Napoleon's commission to build a 600-cell battery at the Ecole Polytechnique in Paris.
- An NGO funded project financed the building of a 2000 cell battery by the Royal Institution of London in 1808, using funds raised by donations to a subscription fund at the Royal Institution of London.
- Humphrey Davy used the Royal Institution's 2000 cell battery to create an electric arc between two electrodes, an early experiment that led to the use of electricity as a source of lighting.
- These early NGO and PPS funded experiments led to several commercial applications focused on chemistry with experiments that isolated elements. Early batteries were also increasingly used in commercial electroplating.
- The widespread use of the telegraph required significant refinements to the battery. Morse secured $30,000 in PPS funding from the US federal government to construct an experimental telegraph line from Baltimore to Washington. This proved that such lines were feasible and helped to overcome the resistance of private investors to risk funds in telegraphic development.
- By 1850 there was 12,000 miles of telegraph, much of which was financed by FPS firms. Nonetheless, in 1861 the U.S. government subsidized the building of a transcontinental telegraph line which was completed in 4 months.

Lesson

- These developments show how mistaken is the view that the public sector had little influence on the invention and early applications trajectories of electricity before the mid-19th century.

Rural electrification: Profit incentives were lacking for rural electrification. In the 1930s, the US government under the New Deal assumed a responsibility that the private utilities had been unwilling to assume and that they continued to resist until they saw the futility of their actions. The demand for electricity from farmers began at a low level because their capital equipment was not set up for electrification. Over the years as new equipment was purchased, such as electric milking machines and refrigeration facilities for home and barn, demand rose dramatically. Farm efficiency rose correspondingly. From 1935 to 1966 the government-financed initiatives increased the proportion of electrified farms from 11% to 98%. Finally, when all the long-term adjustments had been made, the demand became such that subsequent provision of electricity became a paying proposition for the FPS.

Lesson

- Rural electrification is a common case in which the eventual massive payoff was too far off and uncertain for the FPS to do the financing but when the PPS did the job, both the social benefits and the FPS's opportunities were enormous.

Computers

The "Turing Machine" was a device conceptualised by Alan Turing in 1936 while studying at Princeton University. There were several subsequent inventions that were largely NPS with NEO (military) funding.

Prior to World War II, Turing was employed by the Government Code and Cypher School, the Universities of Cambridge and Manchester and the National Physical Laboratory. Then with British government finance, he first created a mechanical computer in 1940, then the electronic Colossus Computer in 1943.

The Harvard Mark I (1944) was funded and built by the FPS (IBM). The ENIAC (1946), built by the US Army's Ballistic Research Laboratory, is considered by many to be the first electronic computer although a German one and Turing's predated it.

The fundamental breakthrough of stored-program-architecture computers was incorporated in three machines that were almost completely financed by the NPS, two in UK universities and one in the US (by the army).

The first fully operational stored-program computer in the U.S. was the SEAC built by the National Bureau of Standards in 1950.

The IAS computer built in 1951 by von Neumann at the Institute for Advanced Study was funded by various PPS and FPS sources including the US Army, Navy and RCA.

A great deal of PPS funding was channelled through the Bell Labs which, as already observed, is an organisation that cannot be classified as being wholly in the

FPS. The Lab was formed by Alexander Graham Bell in the late 19th century.[10] In 1925 it became the Bell Labs owned by the American Telephone & Telegraph Company (AT&T). Initially, it was entirely funded by AT&T.

> "During World War II, Bell Laboratories undertook more than 2000 research projects for the Army, Navy, and the National Defense Research Council. Between 1949-1959, the U.S. Government funded more than $600 million of research at Western Electric and Bell Laboratories (approximately 50% of total Research Budget of Bell Laboratories.) During this period the Department of Defense allocated between $1 million and $2 million annually to over one hundred doctoral candidates working on basic research of solid-state physics. Between 1949 and 1959, about half of the Lab's research budget came from the U.S. government, amounting to over $600 million allocated between Western Electric and Bell Laboratories" (Lojek, 2007, 11)

Post-war efforts to develop software, relied to a great extent on university researchers. NPS support remained important in many software advances from the mid-1950s onward. For example, John W. Tukey who enjoyed NGO support and was credited with coining the term "software", was a professor of mathematics at Princeton for his entire career. He also held a senior position in the Department of Statistics and Data Analysis at AT&T Bell Laboratories.

Lessons

- See next case study

The Internet

The internet is another example of a technology that had significant NPS support for all its trajectories. Indeed, the invention trajectory was mainly NPS financed and we only touch on a few illustrative highlights below.

The U.S. Air Force financed RAND and the Congressional financed National Science Foundation (NSF) formed the foundation of support for what was to become the Internet. Its development was initiated by the US military's Advanced Research Projects Agency (ARPA) in 1969 (ARPA was established by the US DoD in 1958 and in 1970s it was renamed the Defense Advanced Research Projects Agency, or DARPA.)

Although military services were the largest historical funder of the Internet, and of the post-war development of the computer, more generally, development

[10] Carlaw and Lipsey, forthcoming outline the complex history of the lab from its inception to the present.

efforts were widely dispersed through academic/research institutions and industry partnerships.

> "90% of all good things that I can think of that have been done in computer science have been funded by [ARPA] ... The basic ARPA idea is that you find good people, give them a lot of money and step back. If they don't do good things in three years, they get dropped."[11]

The PPS funded SAGE 'computer', began as a research program in 1954 for the US Air Force, was effectively the first Local Area Network. AT&T did much of the work, but the funding was all provided by the PPS.

Other networks that were formative for the Internet, and which were NGO and PPS supported include Merit Network, CSNET, NSFNET, CYCLADES, SERCnet, and International Packet Switched Service (IPSS). Funding came to a great extent from the National Science Foundation. Also important were the French *Institut de Recherche en lnformatique et en Automatique*, the International Telecommunications Union (a United Nations special agency) and SERCnet which linked together British universities and research centres, the British Postal Service, and the FPS entities, Western Union International and Tymnet. These are merely representative of the many early networks that evolved out of NGO and PPS supported activities.

In 1991 the World Wide Web was established with the creation of HTML and HTTP[12] by two physicists at the PPS funded CERN laboratory in Switzerland. Although DRAPA approached AT&T and IBM to build a network, both companies declined the request believing that such a network was a threat to their business. But with the help of the state-owned British post office, DRAPA successfully networked various stations from the West to the East Coast (Mazzucato: 111). The NSF initiated the development of the first high speed digital networks in the US.

The web's creation began the explosive commercialization of the Internet. The National Science Foundation was authorised to support the development of computer systems for uses other than those in research and education. Graduate students at the NGO-funded University of Illinois National Center for Supercomputing applications developed a free Internet browser. Although NGO and PPS support has continued to develop infrastructure and bandwidth to

[11] Rao and Scaruffi (2013) quoting Alan Kay.

[12] The acronyms represent Hypertext Transfer Protocol (HTTP) and Hypertext Mark-up Language (HTML).

encourage access, FPS supported innovation has largely been driving the development of applications.

Lessons from computers and the Internet

- These two cases provide a prime example of cooperation between the NPS and the FPS in developing new technologies. It is doubtful that either sector could have done all of this on its own.
- The absence of both direct NPS motivation for national prestige and of top down, politically directed agendas have contributed to the success of the cooperation between the two major sectors at all stages of the trajectories of computers or the Internet.
- NFP support for any science-based new technology seems to be more important in the early stages of development while the FPS can take over much of the effort in the later stages−although as illustrated by the Apple case considered earlier, even the later stages may require science-based advances that are mainly developed in the NFP sector.

Lasers

PPS support for the laser was motivated originally by military interest in a direct energy weapon. Although this program failed, the laser was an unforeseen, huge success in many other applications, both military and commercial.

The bringing together of significant scientific expertise enabled many technological breakthroughs that were organized under the umbrella of laser research. This also complimented other research efforts in different but related technologies (telecommunications, computers, etc.).

The Laser is a technology that is complementary to many other technologies: transportation, information and communication, manufacturing, and power technologies, and many others.

Lesson

- Americans are often unaware of the importance of the NPS in assisting inventions and innovations because so much of it has been done by the Department of Defence (and other government departments). Indeed, the DoD has been so important in the past that Vernon Rutan (2006) has argued that that recent developments in the Department’s overall funding and direction threatens the US lead in many areas of technological advance.

Apple Products[13]

> "Jobs has rightly been called a genius for the visionary products he conceived and marketed. But without the massive amount of public investment behind the computer and Internet revolutions such attributes might have led only to the invention of a new toy."(Maszzucato: 93).

From 2006 to 2011 the ratio of Apple's R&D to its sales ranked 11th out of the 13th compared with those of its main competitors. The main explanation of this low ratio in such a successful company is that Apple

> "… concentrates it's ingenuity not on *developing* new technologies and new components, but on *integrating* them into an innovative architecture: it's great in-house innovative product designs are…based on technologies that are mostly invented somewhere else, often backed by tax dollars." (Mazzucato: 99)

Mazzucato (Chapter 5) shows the many relations between NPS finance and some key Apple products. There is space here to mention just a few of these and for a full discussion see Mazzucato's chapter.

The microprocessor: The introduction of Silicon during the 60s and 70s revolutionised the semiconductor industries by the introduction of the microprocessor. The relevant breakthroughs were the result of research carried out in various public and private partnerships at labs including those at DARPA, Bell labs and others.

Hard disc drives: State funded research on two separate projects in Germany and France culminated in the development of the hard disc. The US government's Department of Energy then played a critical role in its further development.

Integrated circuits: Today's hand-held devices depend upon integrated circuits that are better and much smaller than those used in earlier computers. These were first developed in the Bell labs while the commercialization was aided by procurements of the US Air Force and NASA. Large scale demand for micro-processors by the US Air Force was created by the Minutemen programme which allowed the production of devices that were unaffordable in regular commercial markets until further developments lowered their costs.

Click wheels: These, which allowed users to navigate quickly through their music libraries, were first developed at the radar establishment of the UK and greatly improved by work at CERN.

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[13] This and the next section are drawn from Mazzucato (2015).

Multi touch screens: These were based on technologies that were originally underwritten by government funds.

The Internet and HTTP: The development of these technologies by DRAPA was discussed earlier.

The GPS: This was almost wholly created by military funding. DRAPA funded the Stanford Research Institute to develop a search a technology which formed the basis for Apple's virtual personal assistant, SIRI.

Lithium batteries: The original research occurred in the US and was funded by the DoE and the NSF.

Lesson

- “Apple's organisational success in integrating complex technologies into user friendly and attractive devices supplemented with powerful software and mediums should not be marginalised; however, it is indisputable that most of Apple's best technologies exist because of the prior collective and cumulative efforts driven by the state which were made in the face of uncertainty and often in the name of, if not national security, then economic competitiveness” (Mazzucatio:118)

Wind Power

In the 1970s Denmark, Germany and the United States all started massive wind energy R&D projects. The German and US efforts were judged failures prompting much discussion in the US about the alleged inability of governments to pick winners. The Denmark project, on the other hand, was a notable success. Probably the main reason for these different results was the choice of which technology to pursue. Denmark chose a pre-existing aerodynamically heavy-weight technology while the US and Germany chose a lighter weight technology which was more efficient in design but less reliable in operation.

General Electric, which later became a major US producer, had a large number of patents that trace back to US Department of Energy-finance R&D. But when US government slashed support for wind power development in the mid-1980s by cutting the DoD’s R&D budget, the US industry stagnated. Germany then became a leading producer of wind power technologies with the support of substantial government R&D funding.

Lessons

- The early experience of the three national efforts illustrates the uncertainty attached to major inventions and innovations so that no one knows in advance what will succeed until substantial funds are expended in finding out.

- The American debate about picking winners, cantered on the failure of its wind power initiative, illustrates the error in fixing on one failure or success to judge the efficacy of the NFP in encouraging technological advance. Failures and successes are inevitable and the only metric of success depends on valuing the cumulative results of a large number of efforts.
- The results of the later reduction of US support for wind power illustrates how quickly competitive advantage in a new technology can be lost when competing governments are encouraging early developments which need FDPS support to succeed.

A general lesson from all the cases in this section

- One overarching general lesson from these cases is that the major technologies we study have significant co-evolutionary complementarities amongst themselves so that NPS support for any one technology potentially influences the development trajectories of many others. While discerning the relative importance of the NPS in the specific development trajectories of any given technology is useful – and the NPS played a significant role in many cases – it is important to understand that NPS support in the development trajectories of any one technology typically significant positive impacts on the development trajectories of many complementary technologies. This makes the estimation of the direct positive effects of a single technology likely to be an understatement of its overall social effects.

III. NON-SPECIFIC SUPPORT[14]

In this section we consider examples of support that is not tied to specific firms or products.

General Trade Restrictions

None of the countries that industrialized up to the middle of the 20th century did so under completely free trade. Even Britain protected its key textile industry in the 18th century when it banned the importation of Indian cotton goods. It also placed a series of restrictions on manufacturing activity in its colonies and forced exports from them bound for anywhere in Europe to flow through English ports.

[14] The material in this section is drawn from Lipsey Carlaw and Bekar (2005) Lipsey and Wills (1996) and Lipsey (2002).

Virtually all others that became the industrialised countries of the West, including Germany, France, the United States, and the former British Dominions, sheltered their emerging manufacturing industries behind trade restrictions. These were eventually reduced or eliminated, mainly under the GATT, but only *after* the industries had developed (or created) comparative advantage for at least several decades and often for more than a century.

Lesson

- These were broad based policies directed at developing industries whose technologies had already been proven elsewhere. Typically, national champions were not chosen so that the FPS was left to determine through competition which firms would succeed and which would fail. This in contrast with a few other countries where a national champion was given a local monopoly and was content with the profits from that market while making no attempt to compete internationally −firms that failed as soon as some international competition was allowed.

Until recent decades it was nearly impossible for an industry to begin producing an established product in a currently non-industrialised country because the many disadvantages: small initial scale, and the absences both of sufficient human capital in labour and management and of the R&D capacity needed to compete in the fierce world of global competition where ability to produce a string of new product variations is a major tool of competition. (The disintegration of production to international supply chains as a result of the revolutions in communication and transportation late in the 20th century now allows a non-industrialised country to produce a manufactured product that is one small part of a world-wide supply chain while having few if any of the requirements that were needed to set up a full local industry in earlier times.)

Government bodies providing finance of FPS Development

All the government granting agencies come under this heading. In the US these include the Department of Agriculture (USDA), the Department of Commerce (DoC), the Department of Defense (DoD), the Department of Energy (DoE), the Department of Housing and Urban Development (HUD), the Department of the Interior (DoI), the Department of Transportation (DoT), the Department of the Treasury (TREAS), the Environmental Protection Agency (EPA), the National Aeronautics and Space Administration (NASA), the National Science Foundation (NSF), and the Small Business Administration (SBA). Between them they finance large amounts of technological innovation, sometimes done in house but more often by the FPS. Studies of R&D often look solely at where it is located which is often, possibly predominantly, in the FPS. But what happens in the FPS is often NPS financed.

Lipsey and Carlaw's (1996) Study

Lipsey and Carlaw (1996) studied nearly 30 government Industrial Policy initiatives, some of which were designed to pick specific winners while others were more general in application. They drew many lessons from both the successes and failures of these cases. Although they are all now well in the past, the lessons are still relevant today. In this section, we consider their more general cases, while in the next we cover direct attempts at picking winners.

US aircraft procurement policy

The US Department of Defence (DoD) has in the past provided partial and sometimes full subsidization for firms competing to provide aircraft that met required performances. Two great successes were when the military transport KC-135 bore the major share of Boing's development costs of the airframe that eventually went into the 707, the first fully successful long-range passenger aircraft. A second success was when DoD subsidies assisted Boeing in the development of the engines that later powered the 747 Jumbo, even though they were initially designed for a military aircraft that lost out in competition with Lockheed.

Interestingly, the major competitor to the 707 was the British VC-10, a magnificent aircraft with four engines mounted at the tail, instead of under the wings as in the 707. The plane had significant passenger appeal when it flew in competition to the 707 for the first few years of both plane's existences. Unfortunately, the British government insisted that the aircraft have sufficient power to take off from the rather short runways then common in Africa. The extra power needed to meet this requirement caused the plane's fuel consumption to be significantly higher than that of the 707. This one difference was sufficient for the VC-10 to lose conclusively to the 707. Ironically within two years of the launching of the VC-10, many key African runways were extended to accommodate the take-off requirements of the 707.

lessons

- Policies designed to produce inter-firm competition in innovation increase the likelihood of commercial success and reduce exposure to uncertainty.
- Support for fundamental innovation often produces spill overs to related uses.

- Government intervention in pursuit of political economy objectives are dangerous and can easily hinder what would otherwise be a major success.

Early Korean Industrial Policy

Early Korean industrial policy was designed to protect infant industries. Although particular industries were favoured, the policy was neutral with respect to firms. Many large establishments were created with temporary local monopolies. The government's "export situation room" assisted firms in learning and adopting the high standards that were required for successful international competition. Continued support was conditional on a firm being successful in the export market–the so-called 'export promotion policy'. The policy did "... without doubt, assist in propelling South Korea from poverty to relative affluence in a single generation while many other [similarly situated] countries remained stagnant." (Lipsey and Carlaw 1996: 309)

Lesson

- See after next case

Early Indian Industrial Policy

Lipsey and Carlaw (1996) quote from the analysis of Datta-Chaudhui (1990) who compared the success of the Korean industrial policy with the relative failure of the Indian industrial policy up to the early 1980s. Starting from more or less equal levels of development in 1950, Korea progressed dramatically while India remained relatively stagnant during that period. Three reason for this difference in performance were singled out. First, India inherited an efficient bureaucracy from the British but not one that was oriented toward commerce, while Korea developed its industrial policy bureaucracy from scratch and staffed it mainly with members of the business elite. Second, Indian industrial policy had a large number of sometimes opposing objectives, which required heavy control of the activities of individual firms. In contrast, Korean policies were narrowly defined on export promotion and gave more autonomy to individual firms. Third, India's industrial policy allowed losses to be absorbed by the public sector and had no strong mechanism for rewarding success, in strong contrast with the characteristics of Korea's export promotion policy.

Lessons

A comparison of the two early post WWII industrial policies suggests several lessons.

- Policies need to be flexible. Using the market as a criterion for success and a penalty for failure introduces much more flexibility than when the apparatus of the command system is mainly used.
- Multiple Objectives are dangerous. The single criterion of export success for Korean firms contrasted dramatically with the multiple, often inconsistent, criteria of Indian policies.
- Protection of firms entering new markets can be useful but is also dangerous. New firms in newly industrialising countries often have much to learn about international standards so that protection can give them time to develop the necessary human capital. But if not eventually required to attain international standards they can turn into locally protected failures.
- Policy intervention is best when guided by private sector knowledge. There is room in a market-oriented economy for substantial government intervention, provided it is focused towards, and administered within, the confines of a market orientation. In contrast, bureaucratic control with little discretion for firms to respond flexibly to market signals and to compete in innovations, tends to produce poor results.

Indian public trading companies

One successful Indian industrial policy over the period just considered is the public trading companies. “They are horizontally integrated across several industries and provide a mechanism for importing inputs, disseminating technology and exporting manufacturing goods. They appear to have been successful in diffusing technology and disseminating information that would otherwise have been unavailable to Indian firms. (Lipsey and Carlaw 1996: 324).

Lesson

- NPS efforts can be useful for groups of FPS firms where the group is more efficient at some generic activities, such as precommercial research, that apply to all of the member firms than when any individual firm operates on its own..

Procurement in the US software industry

The US Government’s activities in the software industry have been similar to its role in other hi-tech industries such as semiconductors, computer hardware, and commercial aircraft. Two major and highly important contributions to the software industry were (i) an infrastructure of academic experts built largely by government funding and (ii) high industry standards that were imposed by requirements of the DoD but which spilled over into other software developments. Among things, the DoD encouraged competition among various firms to meet specifications on its new projects and repaid the R&D expenses, either partly or in full, of both successful and unsuccessful bidders. Many of the latter went on to use the developments made for their unsuccessful bids in other successful civilian projects.

Lessons

- Government agencies using government money can successfully encourage invention and innovations by carefully specifying conditions to be met by the R&D efforts of private firms.
- R&D capacity built by government procurements can have important spill overs when used later by FPS firms for invention and innovation of quite different products.
- The general public can often be unaware of the importance for economic growth of public funding of technological change because much of it comes through procurement designed for non-economic objectives with growth being an unintended bi-product.

Canadian IRAP

The Canadian Industrial Research Assistance Program has been in operation continually since 1962. It pays staff salary costs of research programmes deemed likely to significantly advance specific technologies by small and medium sized firms; it makes available R&D results developed in its own laboratories; it disseminates relevant information often not easily available to small firms particularly start-ups. IRAP's agents have discretion to make small grants to firms without going through any centralised red tape, which allows for timely distribution of funds. Longer term control is through the track record of agents not the prospects of individual grantees. The long experience of IRAP agents in innovation attempts can often give invaluable knowledge to firms newly encountering development issues because either they, or some of their products, are new. As of 2020 IRAP was providing some of these forms of assistance to over 10,000 Canadian firms annually.

Lessons

- Government can exploit scale economies by providing technological and procedural information to small and medium sized firms that would be difficult and costly for each to discover on its own, as well as giving rise to wasteful duplication of effort.

- Small and medium sized firm often find it difficult to obtain funding for R&D, especially but not exclusively to fill the gap between proof of concept and commercialisation.

West German Small and Medium Enterprise R&D

This program had similar objectives to, although somewhat different procedures from, IRAP. Meher-Krammer (1990) used an econometric evaluation technique to demonstrate that over its five-year life "…the programme successfully induced commercial innovation but not pre-commercial research. According to this evaluation, 60 percent of the program's activity created 'additional' R&D. It also raised the amount and use of R&D personnel in West Germany and created in limited capacity in the firms affected." (Lipsey and Carlaw: 325)

Lesson

- The lessons from IRAP also apply here and emphasis is added to the point that such programs usually are of most value in assisting the innovation of already proven technologies, rather than inventing wholly new technologies.

IV. PICKING WINNERS

In this section we briefly summarise relevant material for the cases in Lipsey and Carlaw (1996) that were more specifically devoted to picking particular winners. As with the previous section, what follows is only a brief mention of the cases that are more fully discussed in Lipsey and Carlaw (1996). The cases are summarised in Figure 3, which is an adaption of their similar figure. Our figure is more sparce than theirs because ours contains only those cases where the policy was to specifically pick winners whereas theirs also includes the more general cases covered in the Section III. Both figures cross-classify the cases according to several criteria: (i) seeking incremental changes in, or large leaps beyond, the existing technological frontier; (ii) designed either to catch up to the existing technological frontier or to advance that frontier; (iii) requiring changes in the facilitating structure that was large, medium or small. Policies that were successful are listed in bold while failures are in Italics.

Figure 3 Picking Winners

FASCILITATING STRUCTURE	TECHNOLOGY			
	INCREMENTAL		LARGE LEAP	
	Catch-up	Leading Edge	Catch-up	Leading Edge
Large	**Korean electronics** **Taiwanese electronics**		**Singapore Industrial Policy** *Japanese commercial aircraft phase I*	*AGR*
Medium	**Japanese commercial aircraft phase 2** **Early Japanese semiconductors**	**SEMATECH** **NACA**[15]	*French micro-electronics* *British computers*	*Concord* *SST (partial failure)*[16] *ALVEY* **Japanese automobiles**
Small		**Stoves in Kenya,** **Boats in India,** **Electricity in Nepal** Consolidated computer Caravelle	**Airbus**	*VLSI*[17] *Japanese 5G*

[15] Discussed in Section 2 above

[16] The effort itself was failure but was successful in recognizing that and halting the effort whereas similar efforts have persisted long after failure was obvious.

[17] This was a failure in its main objective but did produce some valuable spin offs

AGR

The British Atomic Energy Authority (AEA) established 1954 was a centralized agency for conducting R&D and producing nuclear reactors. Its decision-making process was top-down and politically influenced. Initial the British who were world leaders in nuclear technology thought their gas cooled reactors would prove superior to the water cooled reactors being developed elsewhere. By 1957 US firms had proved the viability of light water reactors and the British Central Electricity Board was considering buying these. They were persuaded (ordered?) to go with the gas cooled version that at the time had only been proven in small prototypes. When these did not work well when scaled up to larger versions, the highly costly AGR project was soon ended and US reactors purchased.

Lessons

- Technological advance is highly uncertain and lines that look promising originally may later prove inferior to lines developed elsewhere.
- Constant surveillance and the ability to cut off lines that are proving unsatisfactory are critical, although considerations of national prestige often get in the way of making such hard decision, particularly when the successful advances are being made in other countries.

The Anglo French Concorde

The original Anglo-French agreement to design and build a supersonic aircraft that was signed in 1962 contained no provision for limiting costs or reviewing and/or cancelling the project. Technical problems proved much more difficult than anticipated and by 1973 the costs, originally estimated at less than £200 million, had risen to over £1000 million, much of it spent on unsuccessful attempts to deal with the sonic boom. Also, during the development, it became apparent that the running costs would be very much higher than expected, so high indeed that no airline was willing to accept the plane even as a gift. Eventually only Air France and BA operated the plane, which was taken out of service after its fatal crash in 2000.

Lessons

- Once again, the uncertainties associated with attempting technological advances at the frontiers of knowledge are apparent. Since these cannot be anticipated at the outset, it is critical that mechanisms for reviewing or even abandoning the project are set in place at the outset and that considerations of national prestige be avoided. (After all there is no prestige in hanging on too long to what is proving to be a costly failure.)

The US SST

In 1962 the US decided to develop a supper sonic aircraft to compete with the Concorde. By 1970 when $1000 million had been spent on it, the government decided to drop the enterprise and write off the expenses on the grounds that the first generation of supersonic aircraft was not going to be a commercial success or, if the Concorde was a limited success, there would not be room in the market for two such jets in the near future.

Lessons

- Ability to recognise failure and end an attempt to push the technological frontier is important.
- Being first mover is not always an advantage when looking for a large leap at the technological frontier. The second mover can learn from the first, particularly when the first fails, causing the follower to abandon its attempt, as with the SST, or seriously amend its procedures if the mistakes of the first mover are not inevitable.

ALVEY

Begun in 1982, the British ALVEY program as was intended to establish British leadership in the software industry within five years. The program was politically motivated and created in a 'top down’ fashion with no detailed analysis of the problems of the industry. It was administered by bureaucrats rather than industrial experts while foreign interests and expertise were excluded. It pursued technology for its own sake, ignoring the structural costs imposed on firms and industry. It produced very few marketable products−and those were mainly of use to the military. Importantly, it omitted what many regarded as an essential element, the co-development of both software and hardware technology. Indeed, it was “... a composite study of most other things that should not be done in any technology policy.” (Lipsey and Carlaw 1996: 305).

Lessons

- Multiple objectives are dangerous**.** By going for both pre-competitive advances and commercial viability, the programme failed to account for the difference in motivations and expertise of firms in these two lines have of activity.

- Technology push is dangerous. Precompetitive research needs to be directed towards eventual commercial viability rather than just advancing technology for its own sake
- Policies should exploit the FPS's expertise where possible. The top down approach from bureaucrats with little input from private sector human capital is usually a route to failure.
- It is important to take account of the relation between the technology being pushed and the supporting facilitating structure. Ignoring the link between hardware and software was a disastrous mistake.

The Japanese automobile industry. [18]

The early Japanese industry mainly served local civilian and military markets, but it did have the facilitating structure that serviced a fully developed local industry. We have listed this case as requiring medium changes in structure since, although much already existed, the new production methods required significant changes in the supporting structure.

Three developments were critical in the post-WWII development of a world class industry. The first two were by the PPS (MITTI) and the third by the FPS in opposition to the PPS.

- Import restrictions gave the local market to local firms.
- Foreign automobile firms were barred from locating in Japan, preventing Japanese-based firms from becoming miniature copies of US firms using US technology as happened e.g., in Canada.
- The Japanese firms resisted MITTI's pressure to combine into a few national champions each with a monopoly on specific product lines, thus preserving competition among themselves.

Unable to reach the MESs of US firms in the small local market, Japanese car producers innovated until their MESs shrunk to a size that was reachable in the local market—and *quite unexpectedly* at a cost level below those of American firms operating at their larger MESs.

Lessons

- The uncertainty attached to innovation often makes it impossible to predict how support of an industry will turn out. But maintaining competition among several local firms who are forced to compete

[18] Since this is one of the very few cases in which the NPS picked a winner that required a large technological leap for its success, the case is worth much more in-depth study than here. It can be found in Womack et al (1990).

with their R&D is a key condition for success in most if not al1 cases. A large technological leap, although always fraught with difficulties, is easier if there is a well-developed facilitating structure to support the industry

VLSI

This Japanese project begun in 1976 was intended to develop breakthroughs in semiconductors by targeting pre commercial research. By facilitating the transfer of knowledge between firms, it encouraged co-operation that accelerated such research while preventing wasteful duplication. The project failed to create genuine breakthroughs but did produce a considerable number of technological spinoffs that helped Japanese firms in their competition with American firms.

Lesson

See below

Japanese (early) 5G

The early Japanese Fifth Generation (5G) Computer project sought to create intelligent (AI) computers. The project failed to achieve its technical objectives and was terminated after four years. However, the spill overs from the research effort had significant positive effects on the competitive success of many private companies.

Lesson from the above two cases

- Both the early 5G and the VSLI programs illustrate the hazards in attempting leading edge breakthroughs while also showing that even failures in the main objective can produce spill overs of considerable value to many firms but which may or may not be enough to justify the original policy had the end results been known at the outset.

General lessons on attempted large leaps at the lending edge of technology

- The uncertainties and high risks associated with attempts at making successful breakthroughs at the technological frontier are illustrated here by the six cases in which the main objective was not achieved. Indeed the one successes, the Japanese automobile industry, was achieved *quite unexpectedly* when the efforts to reduce the minimum efficient scale for Japanese firms to well below that of American firms led to that MES being at a significantly lower unit cost that for US firms at their higher MESs.

Singapore Industrial Policy

As a result of the Singapore PPS's ability to pick, not just one, but multiple winners, the country was transformation from a relatively underdeveloped economy, with no obvious comparative advantages in manufacturing at the time of its independence in 1965, to, well before the end of the century, a highly developed, relatively high income and prosperous economy based on created comparative advantages in a number of high value added manufacturing industries. Under its industrial policy Singapore became

> "... a high-tech island, which has several times diagnosed industrial trends and emerging technologies 5 to 10 years before anyone else−for example, software in 1978 and multimedia and wireless communications in 1990. Within the constraints of its limited human resources, Singapore conceived and implemented an S&T strategy in the early 1980s that involved attracting high that high- value- added technology and knowledge-based industries such as software, computing service industries, financial services, and medical consultancy services. This strategy consisted of three sets of interrelated measures: development support measures directed at these new industries, export support, and human resource training. (Lipsey and Wills 592-3). [19]

International consultants were used to identify promising new developments which were accepted by locally based firms. These were originally foreign owned multinationals but increasingly they became locally owned firms (but not a single national champion). PPS concerns was on economic growth rather than national prestige *pe se* −prestige that came as a bi-product of economic success not an up front objective.

Lessons

- Comparative advantage can be changed endogenously
- Successful industrial policies typically rely on close cooperation between the PPS and the FPS.
- It is often better to identify and support niches for productive development rather than searching for dramatic achievements in competition with established foreign multinationals. It is important to avoid creating a single 'national champion' monopoly with a monopoly in the local market.

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[19] For a full discussion of the methods used for this highly successful industrial policy see Lipsey and Wills (1996).

- Cooperation between the FPS and the PPS is important with the FPS being willing to risk funds in any PPS supported enterprise.

Japanese commercial aircraft (phase one)

Starting at 1954, the Japanese attempted to build a commercial airline construction industry. As well as designing a new aircraft, the entire facilitating structure of supporting firms and human capital had to be created. Furthermore, the local market, unlike that for automobiles, was too small to support several competing firms, competition among whom typically encourages innovation. Private firms were unwilling to risk their own money unless supported by substantial government funds. One aircraft was produced, which was, although a modest technical success, a commercial failure.

Lessons

- Attempting to build from scratch a new industry, including its entire supporting facilitating structure, is dangerous and to be avoided except in rare cases.
- A good indicator of the potential of some new project is that FPS firms who will be involved are willing to risk substantial amounts of their own funds in the enterprise.

French Microelectronics

French policy has typically targeted high-profile technology meant to make France a world technology leader. The most widely used method has been the establishment of a national champion in the targeted industry. These champions were either private monopolies supported through government R&D funding or state-owned operations. All such top down attempts to compete with well-established US firms were failures. Indeed one small, successful French semiconductor firm SESCOSEM, was ordered to take part in one of the French PPS initiatives by vastly enlarging its capacity to an extent that it found impossible. This led to its eventual failure with the end result that there was less made-in-France technology of this sort than before the PPS intervention.

Lesson

- See next case

B**ritish Support of the Computer Industry**

In the early 1960's, the UK government sought to establish a world-class industry that could compete with IBM. Many smaller firms were forcibly merged into one national champion, ICL, which was given domestic protection through government procurement. The policy failed. Although their ICL computers were originally significant technical achievements, they fell behind IBM products and eventually could not compete with them on the open market. In the meantime. several UK operations, including some universities and government departments, had their research hampered by being forced to buy British rather than American computers.

Lessons

- Both the British and French failures are object lessons in what not to do in industrial policy. Here are just of few of the many lessons that are suggested by these case studies:
- Setting up a new industry to compete with an established giant located in another country is highly dangerous.
- Establishing a national champion rather than allowing several firms to compete with their R&D and marketing is often, probably in most cases, a mistake.
- Policy should take account of the relation between technology and the facilitating structure. The British and French structures were suited to supporting small nitch-products rather than the major one.

Airbus

This was formed as a consortium of European aircraft firms intended to challenge Boeing's dominance in the industry. It was initially a large, catch-up, technological leap, then followed by continued, incremental, leading-edge improvements as competition in technology between Airbus and Boeing continued over the decades. Although Airbus required a significant leap forward in domestic technology, it was one for which the Europeans had an existing facilitating structure in the form of several major aircraft firms, many component manufacturers, and much human capital.

The management of Airbus Industries (AI) was left to the industry itself without the top-down interference from the PPS that had caused failures in several other technology pushes in both the UK and France. The main PPS contribution has been in providing finance, usually as subsidies for development costs. Although it failed to cover even its direct production costs on its earliest aircraft, it has done so on some successful later versions. The development subsidies were comparable to, but probably exceeded, those that Boeing received among things as military contracts that covered development costs for the airframe of the 707 and the engines for the 747.

Its latest plane. the A380, is the largest commercial jet flying. Although a technological success, it is a market failure, largely due to an unforeseen shift in airline practices. When it was designed, long distance haulers used high-capacity aircraft to take large numbers of passengers to hubs where they transferred to smaller, shorter-range aircraft to reach multiple destinations. In this market the bigger the long-haul aircraft the better. But the development of long-range smaller capacity aircraft changed procedures by increasing the use of long-haul, lower-capacity, direct flights to smaller destinations. Although unforeseen when the A380 was being developed, it illustrates the major uncertainties associated was attempted major breakthroughs on the leading edge of technology.

Although the extent of the success of Airbus as an FPS firm is debatable, it has created a worldwide duopoly in the passenger long and medium range aircraft industry that would probably have otherwise remained a Boeing monopoly. Also, although the value of the extra innovations resulting from the competition between these two firms, compared with what a Boeing monopoly would have produced, is hard to quantify, it is undoubtedly positive.

Lesson

- One circumstance in which governments has a reasonable chance of picking winners is where the FPS has the necessary, fully developed facilitating structure and the PPS provides the necessary funding, particularly at the early stages of development, leaving the management fully in the industry's hands.

Sematech[20]

Semiconductor Manufacturing Technology is a consortium originally comprised of 14 American chip makers that was set up in 1988 at a time when Japanese firms were leaders in the semiconductor industry. Assisted by substantial government funding, its objective was to allow American industry to compete effectively with the Japanese. In was a success in, among other things, helping to reduce significantly the R&D necessary to develop each new generation of chips and reducing miniaturizing cycles from 3 to 2 years.

> “Sematech has become a model for how industry and government can work together to restore manufacturing industries—or help jump-start new ones. [Recently Sematech] managed a new Photovoltaic Manufacturing

[20] This section. Including the quotation is based on Robert Hoe (2011).

Consortium funded by the industry, the Department of Energy, and the state of New York. With a mission to help develop a new kind of photovoltaic manufacturing technology…[one that] again places Sematech in the role of revitalizing a key industry."

Lesson

- PPS-FPS cooperation is almost always better than a top-down solely PPS funded initiative.

Three Small Scale Successes

Stoves in Kenya

In the 1980s, Kenya faced a problem of dwindling wood supplies. After detailed studies, The Kenya Renewable Energy Development Project (KREDP) developed the new stove technology that used oil and chemical drums to produce stoves with greatly increased energy efficiency, but which did not require changes in household use patterns. This was assisted by a further innovation: a mobile training facility which was able to reach the widely dispersed artisan labor force. As a result of the program, consumption of wood and the environmental threat fell, and workers required for the growing industry that produces the stoves were successfully trained.

Boat Building in India

Between 1978 and 1983 Indian boat prices doubled due to an acute shortage of wood supplies. The PPS Centre for Appropriate Technology (CAT) and an FPS firm, developed and diffused the technology for building plywood boats which use fewer trees per boat than the traditional technology. Several design problems had to be overcome and several refinements made in response to feedback from fisherman using the new boats. The program successfully overcame the materials shortage while improving productivity and profitability in the region's boat building industry. The industry grew under competition from firms in the FPS.

Electricity in Nepal

Nepal's Micro Hydro Project was initiated in the early 1960s when the main technology for milling was either diesel or water powered mills. A new technology was developed in the PPS to meet the varying characteristics of the landscape. Several small companies in the FPS began to produce these new turbines. The program has met its objectives of providing crop processing based on waterpower and assisting rural electrification.

Lesson

- These three cases illustrate the possibilities of successful PPS financing in small but social beneficial advances that work within the country's existing facilitating structure.

Consolidated Computers

This was a Canadian success turned into a failure by bureaucratic interference. The company was established to market a new data processing-invention called Key-Edit. By 1969, it had gone public, employed 200 people, and had annual sales of $650,000. The management applied to the PPS's General Adjustment Assistance Board (GAAB) for a loan guarantee to secure financing needed for expansion. This allowed CCI sales to explode causing cash flow problems. While the demand for CCI's product was strong, its balance sheet looked weak for understandable reasons. GAAB, however, insisted that the management surrender control of the company to the GAAP, as the price of providing temporary assistance. At that point (1971), the government had put $7 million into the firm. Fearing that a write off would be an admission of mistakes, GAAB kept CCI in business. By now the company had lost its technological lead and was unable to maintain a competitive position despite large R&D investments. Ten years later the government ended its involvement with losses of $120 million.

Lesson

- What is almost always a major government mistake is attempting to intervene in the detailed operation of any firm. In the case of CCI, the firm was much better positioned, by virtue of industrial background and innovative abilities, to manage the matters, than was the government, which made several further mistakes leading to failure of the company.

Korean Electronics

The modern Korean electronics industry was created after 1969 by government policy. Local producers we're encouraged to engage in licencing agreements with established electronics manufacturers in other countries for technologies that fit into the existing Korean facilitating structure, not for leading edge new technologies. The policy allowed Korean firms to exploit their comparative advantages in labour intensive manufacturing while also accumulating foreign knowledge. Korean firms exploited licencing arrangements in many downstream technologies while developing the flexibility to change technologies as circumstances changed. Both local production and exports rose dramatically in the subsequent decades.

Lesson

- Cooperation with established foreign firms can be beneficial to the home country if these firms are willing and able to transfer their human capital to the home firms which are given incentives to incorporate it.
- Adopting niche technologies that fit into the existing facilitating structure can often be more successful than attempting breakthroughs at the technological frontier.

Taiwanese electronics

The Taiwanese government created an electronics industry through several initiatives.

- The creation of a wholly new industry through government agencies, rather than government support of private firms.
- Government organisations licensed foreign technologies then sub-licensed them to local industry.
- The industry was fostered by public assistance until mature enough to be commercially viable. Much of it was then transferred to the private sector.
- The government persuaded Phillips to enter a joint venture with several small Taiwanese manufacturing firms that had been pulled together by the government into the Taiwan Semi-Conductor Manufacturing Corporation.

The policy of targeting the electronics and information industry was successful. Taiwan developed the largest pool of chip design talent in Asia outside of Japan.

Lesson

- There are no simple rules for Industrial Policy. Taking on the established giant in the US would have seemed a route to failure in Taiwan. However, several policies worked towards success even against heavy odds for failure. The government owned firms cooperated with established US firms making technology sharing a requirement. Emphasis was on success in the international market and support was withdrawn if that was not secured. Once the firms were transferred to the private sector, they had to compete with each other as well as succeeding internationally.

Japanese Commercial Aircraft, Phase 2

MITI's response to the failure of its Phase 1 plans was to drop the idea of a

Japan-only industry and look for foreign partners with Japanese firms playing a smaller role, first in engine design and later in airframes. The joint ventures have succeeded but Japan still lacks a "complete" large commercial aircraft industry.

Lesson

- Successful policies often seek to establish niches in established international industries rather than to develop the entire industry–niches for which the local facilitating structure of human capital and local firms are well adapted.

Early Japanese Policy Towards Semiconductors

Early in its post war development MIITI targeted the semiconductor industry as key to its development. Early Japanese catchup policies encouraged licencing agreements for established technologies developed in other countries. By choosing established technologies, uncertainty was diminished while identified niches could be filled. There were tax incentives and subsidies for successful firms plus some protection of the home market from foreign competition. Pre commercial R&D was coordinated centrally. This prevented wasteful duplication and allowed all firms to have access to the pre commercial discoveries of any one of them. The subsequent growth of the Japanese industry and its movement to higher value products illustrated the success up this early infant industry programme.

Lessons

- Licencing of established products can reduce uncertainty especially at the catchup phase of development.
- Mechanisms adopted by the PPS to encourage and pool pre-commercial research that is done by FPS firms can be extremely valuable.
- Incremental development of an industry to grow organically through the niches where it has or can easily develop the requisite facilitating structure can often be superior to attempts to leap quickly to a full grown, multifaceted industry holding its own against established international competitors .

Some General Lessons from Attempts at Picking Winners

1. There is enough uncertainty in technological change that the policy of picking winners is bound to back some winners and some losers. Assessments of this NPS policy need to consider the overall experience, not just the success or failure of one enterprise. (See e.g.

the failures of the Germans and Americans and the success of the Danes in developing an early wind driven energy source.)

2. More important than picking winners is the ability to eliminate losers. (Examples of where the PPS persisted with “champions” well after failure was obvious include: Consolidated computers, Concorde. Examples of where the PPS support terminated once the non-viability of the “champion” was obvious include: United States SST and Japanese early 5G.)
3. Bureaucratised decision processes have led to massive failures whereas success is more common when the public sector selects winners in close and sustained consultation with the private sector backing and assisting those efforts that the private sector is willing to back with its own funds. (Failures: French micro-electronics, British computers. Consolidated computers, Japanese commercial aircraft (phase 1).)
4. Picking winners is much easier in catch up than in leading edge developments, especially when the desired technological change is incremental. (Successes: all the items in the *incremental Catch-up* column of Figure 3.)
5. It is easier to create a catch up winner in a niche technology where there are many different products and producers than in a technology in which there are only one or two competing producers against whom the new entrant must come into direct competition. (Failures: British and French electronics and computers in competition with IBM.)
6. Going for a winner that requires a large leap in both technology and the facilitating structure is unlikely to be successful. (Failures: all of the cases in the large leap leading edge column of Table 3 with the exception of Japanese automobiles.)
7. Successful policies often pursue incremental innovation and where possible aid in the acquisition of tacit knowledge. (Success: Japanese Commercial Aircraft Phase 2.)
8. By targeting small, leading-edge innovations that work within a country's existing facilitating structure policy makers can maximize the commercial and social benefit of new technologies while at the same time reducing the exposure to uncertainty by minimized the number of supporting technical and structural innovations that were required. (Successes: Stoves in Kenya, Boats in India, and Electricity in Nepal)

V. CONLCUDING REMARKS

The cases considered here reveal the close relation between the FPS and the NPS as they cooperate to create technological change and economic growth. These cases are but a few examples of the many that could have been considered. Nanotechnology and biotechnology are two additional cases where the overall trajectories, if not their details, are clear and the FPS and the NPS work closely together to encourage all of the technologies' trajectories. Another example is US pharmaceutical industry where the FPS firms earn enormous profits while seldom admitting the extent to which new drugs are developed from NPS research.

If they do nothing else, the cases considered here reveal that those who would dismiss industrial policy with the statement "Governments cannot pick winners" are relying on an empty slogan to avoid detailed consideration of the complicated, multifaceted relationship between the private and public sectors in encouraging the inventions and innovations that are the root of economic growth.

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