1 Introduction

The economy is an evolving system whose modern output trajectory has consistently shown trend growth, at least since the First Industrial Revolution that began in the mid eighteenth century.[*] Economic historians agree that technological change is the main driving force for this growth. Without it, growth would soon approach zero, ushering in what the Classical economists called the stationary state – the end of economic evolution. Joseph Schumpeter saw the entrepreneur as the main agent of technological change. However, finance is a necessary enabler of the actions of entrepreneurial agents, whether they are individuals or members of larger organisations.

Our concern in this Element is with the sources of the finance that enables technological evolution. Specifically, we ask: to what extent does the financing come from profit-oriented firms and individuals in what can be broadly called the private, for-profit sector, or from others who are not primarily profit oriented, located in what we call the not-for-profit sector? To this end, we divide all sources of financing into two groups: the for-profit sector (FPS) and the not-for-profit sector (NPS). We investigate the roles that agents in each sector have played, both directly and indirectly, in financing the creation and evolution of twelve major technologies that were innovated between the late nineteenth and early twenty-first centuries, many of which have been labelled general purpose technologies (GPTs).[1] We describe the development of our selected technologies in considerable detail, gathering from disparate sources many things that are already well known. Doing so emphasises four things that are not obvious in many discussions of industrial policy: (i) the extent to which agents in the NPS and FPS provided the necessary finance, sometimes in isolation from and sometimes in cooperation with each other; (ii) both the variety and the timing of the support that NPS agents have given to the technologies examined here; (iii) both the unexpected successes and failures that agents in both the NPS and FPS have encountered because they are dealing with inherent uncertainty; and (iv) that new knowledge does not diffuse instantly and costlessly throughout the whole economy. Studies of *the physical location* of research and development (R&D), inventions, and innovations typically give heavy weight to the FPS and

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[1] The method of qualitative analysis employed here is referred to as 'appreciative theorizing' by Nelson and Winter (1982) and is related to process tracing used by social science researchers who deal with qualitative data (e.g., Befani and Mayne (2018)).

much less weight to the NPS. However, when we study the sources of *the finance* that enabled these technological developments, this greatly increases the relative weight attached to the NPS compared with that of the FPS.

Section 2 considers how two views of the economy, the Neoclassical and the evolutionary, influence attitudes to public-sector support for technological inventions and innovations.

Section 3 deals with some preliminary concepts and definitions. We distinguish four trajectories in the evolution of any new technology: the *invention trajectory* covers the scientific and technological developments that precede the emergence of an identifiable technology; the *efficiency trajectory* is the time path of the cost of producing a unit of the service provided by the technology; the *applications trajectory* is comprised of the technological products, processes, and forms of organisation that depend on it; the *diffusion trajectory* is the spread of the technology to uses in other places and other times, both nationally and internationally. For each of these trajectories in each of our twelve technologies we indicate which developments were financed mainly by the NPS, mainly by the FPS, or, as is often the case, by some combination of both.

Section 4 gives a detailed analysis of the major technologies that we have studied, together with some lessons that we derive from each case study. We divide our technologies into five main groups (groups that were discerned after completing our case studies rather than being imposed a priori): Group 1, *little NPS support except for the applications trajectory*, the internal combustion engine; Group 2, *NPS support mainly for the invention trajectory*, refrigeration; Group 3, *NPS support mainly for the efficiency, applications, and diffusion trajectories*, railways, automobiles, aircraft, and agriculture; Group 4, *NPS support mainly for the invention and efficiency trajectories*, the iron steamship; Group 5, *NPS support for all trajectories*, electricity, computers, the Internet, and lasers.

Section 5 presents more general lessons that apply to most or all of the technologies. Two examples follow. First, the more a technology depends on science, the larger the place for NPS support for the relevant trajectories. Second, major technologies have significant coevolutionary complementarities among themselves. As a result, NPS support in the development trajectories of any one technology has significant positive and often impossible-to-foresee impacts on the development trajectories of other technologies, including some that were not directly supported by the NPS themselves. Investments from the NPS can also help to create positive feedbacks through these indirect impacts by creating further complementarities that subsequently operate on the originally supported technology. Thus, calculations of the return to NPS support for a particular technology typically underestimate that return unless they account for the impact on the entire interconnected, complementary system.

When we began our study, we had no strong view on the sources of financing other than the general feeling that the public sector might be a more important source than is often acknowledged in popular debates about industrial policy. We were surprised, therefore, to discover just how important public sector finance has been and how interrelated it has been with private-sector finance in most of our cases. We conclude in Section 6 that dismissing industrial policy with statements such as 'governments cannot pick winners' relies on an empty slogan to avoid detailed consideration of the actual complicated, multifaceted relationships between the private and public sectors in encouraging the inventions and innovations that are the root of economic growth.

2 Policy Implications of Two Views of the Economy

2.1 The Neoclassical View

The Neoclassical view holds that the place of the NPS is to provide a level playing field and remove market imperfections, leaving the FPS to generate an efficient allocation of resources and an optimum amount of economic growth. An important class of market imperfections arises from externalities, often called third-party effects. These are measurable benefits (positive externalities) and costs (negative externalities) conferred by an initiating agent on others. They are effects that the initiating agent has no incentive to consider and, in the case of beneficial new technological knowledge, are usually assumed to be costlessly and instantaneously conferred across all agents. These can be offset in principle by imposing on the initiator a tax equal to the cost, or a subsidy equal to the benefit, that they confer on others. Kenneth Arrow (1962) points out one important source of (net) positive externalities, the introduction of generally available new products and processes. These externalities result in a suboptimal amount of R&D. This provides a reason for the NPS to subsidise R&D to ensure that the amount gets closer to the social optimum. Assuming that the decision environment is characterised only by risk rather than by uncertainty, the FPS will optimise by equating the expected marginal products of all lines of R&D. The NPS role that is then justified is a generalised and hence 'non-distorting' support given equally to all R&D (as a subsidy or tax relief).[2]

[2] 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 of these will raise the value of whatever social objective function is being considered.

2.2 The Evolutionary View

One intellectual basis for supporting NPS activities that go beyond what is sanctioned in the Neoclassical view is found in the evolutionary view of the economy. Without going into detail here, this view emphasises three important aspects of the economy: (i) pervasive uncertainty; (ii) that new knowledge does not, as assumed in Neoclassical economics, diffuse instantly and costlessly through the economy, as is shown in many of the cases described in what follows such as early aircraft-related research, the Korean electronics industry and Korea's adoption of lean production techniques; and (iii) the endogeneity of both technological change[3] and, at least to some extent, scientific research.[4]

The fact that inventions and innovations are fraught with uncertainties upsets the idea that the private sector will (with the appropriate, generalised NPS support for R&D) allocate resources, including R&D, in a socially optimal way.

> Research into technological change (see especially Rosenberg 1982, 1994 and 1996) establishes that uncertainty is always present and often pervasive in the search for new technological knowledge. One cannot even enumerate the possible outcomes of various lines of R&D devoted to inventing and innovating some new technology. Large sums are sometimes spent with no positive results, while trivial expenditures sometimes produce results of great value. Furthermore, the search for one objective often produces results relevant to different objectives. (Lipsey, 2013: 44)

Thus, rather than maximising the expected value of profit from all lines of activity, including R&D, firms should be seen as groping into an uncertain future in a profit-oriented but not profit-maximising manner. Indeed, as the detailed discussions of our technologies illustrate, all agents, regardless of sector and motivation, who seek to effect technological change should be regarded as groping into an uncertain future.

The fact that technological change is endogenous (influenced by actions in both the FPS and the NPS) undermines the view that the socially optimal policy action is to allocate resources efficiently *given the current state of technology* – as the Scottish-born Canadian economist John Rae (1905) pointed out long ago.

Since it denies the existence of a unique optimum allocation of resources to all activities, including R&D, the evolutionary view opens the way for an empirical evaluation of the pros and cons of specific actions by both the NPS and FPS to encourage technological change and economic growth.

[3] Popularized by Joseph Schumpeter (1942) and documented by many economic historians long before it was introduced into macro models by Lucas (1988) and Romer (1990).
[4] Argued persuasively in Rosenberg (1982, chapter 7).

2.3 Spillovers

Another reason for the conclusion just stated lies in the existence of spillovers, a concept that includes but goes well beyond externalities. Carlaw and Lipsey (2002) provide a definition of technological complementarities that enables the distinction of spillovers that are externalities from those that are not.

> A *technological complementarity* arises in any situation in which the past or present decisions of the initiating agents with respect to their own technologies affect the value of the receiving agents' existing technologies and/or their opportunities for making further technological changes. (p. 1310)

Of course, the initiating and receiving agents may be identical, as when an agent's technological innovation affects the value of that agent's other technologies. Here we confine ourselves to the cases in which the two agents are separate entities. While the aforementioned complementarity refers to technical relations, *spillovers* refer to economic relations, occurring when technological complementarities provide profitable opportunities for agents to exploit previously created technological knowledge. Some spillovers are externalities in the sense that they provide what are at the time identifiable and (at least in principle) measurable benefits to the receiving agents. Others, however, go well beyond externalities, conferring benefits on subsequent agents that may extend over times and spaces that cannot even be identified, let alone measured, at the time of the initiating event.

As our case studies reveal, technological complementarities pervade human-created economic systems of technological innovation, production, and trade. Carlaw and Lipsey (2002) point out that although these technological complementarities drive Arrow-style externalities, where a calculable rate of return exists for a third party, others take the form of opportunities to create novel products, processes, and organisational structures that would not have existed in absence of the originating technology. These spillovers can persist for decades, even centuries. For one example, electricity created both the opportunities for all the gadgets that revolutionised household operations in the first half of the twentieth century and the technologies that created the modern information and communications technology (ICT) revolution, such as telephones, telegraphs, radios, TVs, faxes, electric lighting, computers, email, the Internet, and satellite signals. For another example, the computer in its various forms has been incorporated in a massive number of technologies, including aircraft controls, the Global Positioning System (GPS), automated factories, mobile phones, myriad electronic games, and the Internet, to mention just a few. Similar comments can be made about the laser and many other science-based modern technologies. In all these cases, those who were responsible for the invention and early development of the technology could not have foreseen its many future applications, let alone gain a compensation equal to even a small fraction of the economic value those applications enabled.

The absence of obvious monetary incentives to the original inventors and innovators commensurate with all the economic gains that they will create now and in the future provides a reason for the NPS to support these activities when the spillovers can be at least dimly appreciated, even if not identifiable in detail. Note that by covering all spillovers, this conclusion goes further than Arrow's classic justification for subsidising R&D, which only applies to identifiable externalities.

Although NPS actors are subject to the same uncertainties as FPS agents with respect to identifying spillovers, they typically have different motivations and risk/uncertainty tolerances than FPS agents. Therefore, the two sets of agents can play different (complementary) roles in the financing of the evolutionary development of technological complementarities and exploitation of the spillovers they create.

2.4 Summary

Neoclassical policy advice is quite simple and quite general (as long as we ignore second best), applying to all countries whatever their current circumstances: remove market imperfections wherever they are found. In contrast, evolutionary advice is context dependent, there being no simple set of policy rules that apply to all countries, all times, and all circumstances. Participation of the NPS is warranted in the presence of the pervasive uncertainty and massive spillovers that accompany endogenous R&D designed to advance technological knowledge.

3 Concepts and Definitions

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

3.1 Technology and Structure

Key concepts dealt with in this section are 'technology' and the underlying structure of the economy, which LCB call the 'facilitating structure'. Technology is defined as follows (LCB, 2005: 58):

> [T]echnological knowledge, technology for short, is the set of ideas specifying all activities that create economic value. It comprises: (1) knowledge

> about product technologies, the specifications of everything that is produced; (2) knowledge about process technologies, the specifications of all processes by which goods and services are produced; (3) knowledge about organizational technologies, the specification of how activity is organized in productive and administrative units for producing present and future goods and services (which thus includes knowledge about how to conduct R&D).

This concept of technology distinguishes it from its physical embodiment in capital goods. A particular machine is often referred to in popular discussion as a technology, but the technology is the knowledge of how to make that machine, not the machine itself. Given the knowledge, a competent agent can make the machine; given the machine, the agent might not be able to reverse-engineer it to discover the technological knowledge that went into creating it.

The separation of technologies from their physical embodiments leads to the following definition. *The facilitating structure* is the set of realisations of technological knowledge – that is, the actual physical objects, people, structures, and organisational forms in which technological knowledge is embodied.[5] This separation is important because the evolution of major new technologies is strongly influenced by how well they fit into the existing facilitating structure. Some require large and persistent changes in that structure, while others fit almost seamlessly into it.

3.2 Evolutionary Trajectories

We identify four trajectories that are distinct in principle but sometimes so intertwined that they cannot be dealt with separately in practice.

The *invention trajectory* begins with all the scientific and technological developments that precede the emergence of an identifiable 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. For example, in the case of electricity, this trajectory lasted several hundred years including Gilbert's *de Magneta* in 1600, but having precedents in magnetism dating back much further and ending with the first useful electricity that was not generated by a storage battery.

[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 instruments; (10) government-owned industries; (11) educational institutions; (12) all research units whether in the public or the private sector (LCB, 2005: 60–1).

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More Information

The *efficiency trajectory* of a technology 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 multidimensional array of the costs of these various services.

The *applications trajectory* of a technology is composed of the technological products, processes, and forms of organisation that depend on it – as the electric washing machine depends on electricity – or include it, in one form or another – as when a computer is embedded in a robot.

The *diffusion trajectory* is the spread of the technology to uses in other places, as when computer use 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 applications-diffusion trajectory in what follows.

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

3.3 Agents

We divide agents into two broad groups: those in the FPS and those in the NPS. This second group is subdivided into two groups, agents in non-governmental organisations (NGOs) and those in the public policy sector (PPS). Those in the latter sector are in turn subdivided into two groups according to their objectives, those that primarily seek economic objectives (EOs) and those that seek non-economic objectives (NEOs). Figure 1 summarises:

The FPS 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 microeconomic theory.

The NPS includes all other agents, but we confine our attention to those whose activities affect, either directly or indirectly, the evolution of technologies in their

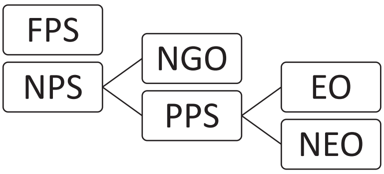

Figure 1 Agent type

invention, efficiency, and applications-diffusion trajectories. Sometimes we treat this sector as a whole but at other times it is useful to consider its subdivisions.

The NGOs include both agents in NGOs and those whose activities are not motivated by a search for profits. We refer to these agents collectively as being in NGOs. They are motivated by such non-monetary incentives as pure curiosity, philanthropy, the pursuit of knowledge, or personal prestige. Their activities, however, create opportunities (and influence evolutionary trajectories) either directly or indirectly, in some cases allowing others to make economic returns. This group includes those in privately funded, not-for-profit, educational institutions (in the United States, some hospitals and educational facilities are for-profit institutions), the church, and privately funded bodies dedicated to the pursuit of scientific and technological advancement, such as the Royal Society and various professional organisations. Many of the agents we consider were educated in schools and universities that were wholly or partially publicly funded. The activities we study had significant NGO support to the extent that these agents' human capital assisted them. We acknowledge this here once and for all and do not go into the educational background of the agents when their contributions are studied.

The public policy sector: this second subcategory of the NPS can be subdivided into two groups distinguished by motivations. The EO includes publicly funded organisations that pursue policies to achieve 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. The EO includes: (i) government departments and other government-financed and directed bodies, (ii) all government granting bodies such as the National Science Foundation, (iii) quasi-independent bodies that are financed by governments but not directed by them in their day-to-day activities, (iv) educational institutions, to the extent that they are financed by governments whether or not they are independent of government policy. The second subcategory of the PPS includes those concerned with achieving NEOs that will benefit themselves, such as military power or election victories. Their activities in pursuit of these objectives often have technological spin-offs that either allow others in the private sector to achieve economic returns – for example, when a new military technology has commercial spin-offs – or allow others in the public sector to achieve their goals that in turn affect scientific and/or technological advancement.

We note some difficulties in this classification of agents.

First, it is not always clear if the activities of self-financed individual agents fall within the NGOs or the FPS. For example, did agents who sought fame for scientific discoveries but subsequently patented and profited from them start in an NGO and move into the FPS, or were they really in the FPS from the outset? Barring much psychological knowledge about motivations, it is often impossible to tell. Fortunately, when the agents were 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.

Second, the boundary between NGOs and the PPS on one hand and the FPS on the other hand is clear enough since the members of the first two groups are not pursuing economic returns that will accrue directly to themselves. However, the boundary between NGOs and the PPS is neither clear nor invariant over time. For example, the PPS and NGOs currently shade into each other as privately funded universities have come increasingly to rely on government funds to finance research as well as other university activities. Although we are interested in distinguishing between the financing that comes from the PPS and from NGOs, it is the clearer division between the FPS and the NPS financing that is most important to us.

Third, by far the most important ambiguity concerns where the boundary lies *within* one major agent – for example, Bell Laboratories – rather than with the general boundary *between* any of our main sectors. The Appendix gives a short outline of some key facts about Bell Labs. These pose a problem for us in that, although its work was mainly financed by AT&T at its inception, the research became increasingly dependent on government financing during and after World War II. 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 fully NPS, FPS, or both.

3.4 Objectives

To document the extent to which technologies have been financed by either or both the FPS and the NPS, we study the evolutionary trajectories for the development of a group of major technologies that came into widespread use sometime after the first half of the nineteenth century. Although our analyses are mostly qualitative, we believe that they throw considerable light on the significant role of the NPS in many of the major technological developments over this