1. The contributions of economics to a science of science policy

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IN SEARCH OF A SCIENCE OF SCIENCE POLICY[1]

The 2008/2009 economic crisis highlighted the importance of science as the foundation of economic growth. In 2009, the US government estimated that a 20 billion investment in research would create 402,000 new jobs in the space of a year, while the achievements of research would set the basis for the creation of new industries and business to meet global competition (Lane 2009).

To serve the interests and well-being of people, science policy needs to be informative. It should be able to provide a set of models, insights, data and instruments that help to crack the world of scientific investigation and ease the work of researchers. Economic and organizational studies of science have made considerable progress in terms of informing and nurturing decision-making in science policy. They have provided theories and methodological instruments to interpret the mechanisms underlying research activities and the role of economics in this has been important. Economic analyses of science and research have grown in number and have become established as the sources of interest that provide background references, offer broad scope, and produce implications. A community of scholars from various subfields is being motivated by a common interest in improving the understanding and functioning of the forces and the means behind the organization of science and by the common purpose of informing and serving policy-making decisions in matters of funding, allocation and efficient use of resources.

Economists have long recognized that scientific and technological advances are among the main drivers of the social and economic development of nations and are a primary means of improving the well-being of society. One of the missions and duties of economics to better serve social and economic progress is to produce new insights, better explanatory

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models, and new instruments for the understanding and appreciation of the scientific enterprise.

In this chapter, we briefly describe the emergence of relevant contributions from various streams of research, their interplay and remix, and their gradual consolidation into a rather homogeneous body of knowledge. We begin in the first section by acknowledging the legacy of four contributions from early economics, philosophy, sociology and history that prepared the fertile ground for the emergence of a the new discipline. In the second and third sections, we review the founding contributions of the functionalist approach to the economics of science and consider some of the recent contributions. The final section concludes and underlines some important areas for future development.

THE ANTECEDENTS

The first important contributions to the economic analysis of science probably came from Charles Saunders Peirce. In his 1876 work (and subsequent developments), he conceived the first, fully-fledged 'economics of research', explaining the conduct and organization of scientific activities. Also notable is the work of Thorstein Veblen ([1918] 1994), who investigated the American universities at the beginning of the twentieth century in search of economic explanations for the institutional behaviour of universities, focusing particularly on the introduction of business principles into university policy.

With the exception of these and a very few other early economic predecessors, it was on the broader front of social science that the themes of speculation and the subjects and instruments used to investigate the economics of science, eventually emerged. A complete overview of the many and influential contributions that contributed to the foundations of this new field would probably constitute a separate book and certainly would exceed the scope of the present chapter. Here we focus on four influencing contributions from philosophy, sociology, history and economics, by, respectively, Michael Polanyi, Robert K. Merton, Derek de Solla Price and Fritz Machlup.

The laws governing scientific enterprise and the behaviour of scientists at the macro level have been the traditional basis of philosophical investigation. Polanyi (1962) produced a fundamental insight that substantially affected future work. In his 'The republic of science' he argued that the behaviour of scientists, who act independently from one another, for example, in choosing their topics of investigation, shows an intimate coordination, which he compares to the 'invisible hand'. This coordination is

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ensured by a set of unwritten rules governing the incentives, evaluation, and rewards of scientists, which is enforced by the authority of the scientific peers called on to evaluate the works of their colleagues. Polanyi saw the criteria upon which these judgements are made as largely consistent with public welfare. This provides the justification to advocate for the complete freedom of science from the political and social authorities and the market, which do not have the same priorities. This theme has often been at the centre of political debate.

The work of Polanyi was developed by Robert K. Merton, who focused on the actual functioning of the rules meant to seal the implicit agreement between science and society. Merton developed a complete and explicit notion of the norms and institutions of science, which he saw as centred on the principles of the *peer-review* and the *priority of discovery*. He highlighted that the social dimension of academic work (for example as represented by individual reputations or the reputations of senior co-authors) often interferes with the smooth functioning of those principles (for example, fair peer review) that ensure coherence of scientific norms in the interests of society (Merton 1968). Merton identified both the norms and their practical implementation, which could cause suboptimality.

Another important contribution is the work of Fritz Machlup, especially his *1962 The Production and Distribution of Knowledge in the United States* and the three follow-up volumes (1980, 1982, 1983, the first three in a planned series of ten curtailed by Machlup's death). *Knowledge: Its Creation, Distribution and Economic Significance* was the first work to underline the increased importance of knowledge as an economic input, anticipating the development of the concept of knowledge/information society. In this work, Machlup tries to map, in a detailed way, the production and use of knowledge in various industries and explain the mechanisms and institutions responsible for the creation, distribution and economic significance of knowledge.

The work of Derek de Solla Price was fundamental to envisioning the emergence of a science of science, supported by a quantitative and statistical appreciation of the phenomenon. De Solla Price trained as a physicist and then became established as an academic historian. He published his citation classic *Little Science, Big Science . . . and Beyond* in 1968, using statistical analysis to isolate and study several facts of science, thereby emphasizing the importance of empirically supported scientific phenomena. His contribution marked a fundamental step towards using statistical indicators as a critical methodological and analytical tool to support science policy. For example, the exponential growth of resources and inputs of science since the eighteenth century, the logistic decay in the pace towards the saturation of scientific trajectories, the uneven distribution of

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achievements in all groups of scientists, and the importance of the social and network dimensions in the production of science (which he called 'invisible collages') are the phenomena he isolated through his meticulous data analysis.

In the 1960s and 1970s, the practice of journal indexing was consolidated and established statistics as a crucial methodology for scientific studies (Garfield 1964). Indexes of articles, authors and citations, initially to help librarians in, for example, bibliographic (re)searches, soon became an extraordinarily powerful tool for the observation and monitoring of science (bibliometric research). The practical work of Eugene Garfield at the Institute for Scientific Information (ISI) included ranking journals, papers and authors, based on article citations, and evolved into the (rather separate) discipline of bibliometrics.

Merton, de Solla Price and Garfield knew each other's work well. Together, they were responsible for a tremendous leap forward in the creation of a science of science policy. This body of methodological work made statistical indicators a suitable – although not perfect – tool to assess and compare scientific achievements, to appraise the diffusion of knowledge, and to measure the impact of science over time. Large-scale, replicable, empirical studies became possible in large pools of data and at the single discipline, group, or individual levels.

THE EARLY ECONOMICS OF SCIENCE

Up to the late 1980s, economists were moderately concerned with issues related to scientific production. They focused mostly on the importance of technical progress as a driver of economic growth. Economists were reluctant to accept science as a suitable subject for economic speculation, in part because of the greater attention that had been given in economic writings to the consideration of equilibrium rather than development, and in part because of the perceived inability of the main economic institutions – namely the markets or a rational planner – to deal with science. Arrow and Nelson give two distinct, although complementary, accounts of why markets are an inappropriate means of allocating resources to science. Nelson (1959) stresses the uncertain nature of research activities. The rate of success in research is very small and its probability is not predictable. Moreover, it is not just the probability of success that is difficult to assess, what would constitute a successful outcome is itself ambiguous. For example, it is frequently found that great achievements in research are the (unintentional) results of activities with a different aim (*serendipity*). In such circumstances, it is not possible for investors or central planners to

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decide optimal budgets for science, or optimal budget allocations among disciplines, according to the principles of economic rationality. Arrow (1962) reached a similar conclusion; he emphasized the public-good nature of knowledge, which makes it impossible to account for the benefits generated by scientific discovery.

Nonetheless, the seminal works of philosophers, sociologists and historians provided a good basis from which to begin to analyse the actual functioning of the institutions in which science is performed and develops, setting aside considerations of optimal investment. By the late 1970s, sociologists had produced a convincing notion of science as a collective effort whose direction is neither guided nor planned by a central coordinator, but whose agents follow a certain economic order. Sociologists had elaborated a notion of scientists as motivated – at least to some extent – by the pursuit of monetary rewards (from careers and public recognition). Their decisions could be seen then as inspired by considerations of the optimal use of resources, which made them suitable rational agents for economic investigations.

The work of Sharon Levin and Paula Stephan (1991; Stephan and Levan 1992) provided a fundamental bridge between the Mertonian sociology of science tradition and the group of labour economists interested in the efficient functioning of the science labour market. In their 1991 work, Levin and Stephan apply the life-cycle theory of decreasing returns from investments, to show that scientists become less productive as they age, net of skills and availability of resources. Their 1992 book refines this finding (by distinguishing between exceptional and average scientists) and broadens the perspective to consideration of the impact of other external factors, such as place and institution, job market and cohort. The rationale for this is that, although we cannot decide what would be the optimal total amount of resources to invest in research, or how much to invest in – say – physics as opposed to life sciences, we should still be concerned about distributing resources to those who are likely to be better placed to use them well. Also, a well-functioning job market is essential for ensuring the retention of scientific talents.

A second fundamental step within the early economics of science field was provided by work speculating on the effect that the peculiar rewards mechanisms in science exert on the strength of the competition in research, for example, among firms competing to innovate products and scientists competing for scientific discoveries (Dasgupta and David 1987). Here, the focus was on the fact that the rewards from research are allocated in a 'winner-takes-all' fashion. This rule, on the one side, is needed to prevent the otherwise public nature of knowledge inducing expropriation (hence weak incentives) and, on the other side, to minimize the risk

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of duplication of effort. In science, this takes the form of the 'priority in scientific discovery', which grants the scientist moral property (Merton 1968). For technology, patents produce a similar outcome (Dasgupta 1988) by granting legal (although temporary) property. In their 1987 theoretical article, Dasgupta and Maskin argue that the implications of the winner-takes-all reward mechanism is excessive competition, excessive risk-taking and homologation in the trajectories of research. These results established the importance of defining property regimes in the scientific achievements that maximize the incentives to engage in science. Later, the debate expanded on the most appropriate regimes of property rights to favour the diffusion of knowledge (Dasgupta and David 1994; Nelson 2004).

We conclude this section by mentioning two excellent surveys, by Paula Stephan (1996) and Arthur Diamond (1996), which define the state of the art in the economics of science up to the early 1990s.

A SCIENCE OF SCIENCE POLICY

Building on these seminal works, a considerable number of later contributions have added to our understanding of science and created a fertile soil for a science of science policy. Fundamental contributions emerged in parallel from several streams of economics. This broadened not only the community of scholars, but also the themes of interest and the pool of approaches, the methodologies adopted and notions used to address the topics. The subsections below describe this growing body of work and the process of recombination and convergence witnessed most recently. It is not possible in this chapter to provide a comprehensive review of this literature, but we highlight what we believe are the most relevant contributions from the various subfields.

Science and the Labour Market

A fairly significant body of work has emerged from the tradition of labour economics and focuses on the science and engineering workforce and the academic job market, which account for the lion's share of the total workforce. The use of survey data, such as the US Scientists and Engineers Statistical Data System (SESTAT), coupled with the widespread use of bibliometric indicators, has enabled numerous quantitative individual-level analyses. For example, Stuart (2006) investigates the relationship between a 'taste for science' and wages, while Ginther and Kahn (2006) enquire into the effect on tenure and promotion in scientific careers of factors such

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as gender, family and ethnicity. Stuart and Ding (2006) examine social networking and exchanges with the industry. The contributions of foreign scientists (Stephan and Levin 2001) and the effect of the international mobility of scientists (Len 2008; Hunter et al. 2009) have also been studied.

Most of this work is based on the US. However, Lissoni and colleagues (2011) have conducted a study which is one of the first works on the European academic job market and is based on individual-level measures of performance. This research models the probability of promotion among a large sample of academic physicists at different career stages, in France and Italy, and shows the responsiveness of career mechanisms to past productivity, to the impact of research, to gender and cohort. The work is important because it provides evidence on recruitment systems and systems of promotion based on a civil-service model of university employment, typical of many European countries. It is expected that more studies of this kind will emerge in the future. The European Union currently is sponsoring several programmes to expand the set of statistical indicators for research, mobility and job markets.

A recent article by Kelchtermans and Veugelers (2011) tackles the problem of how 'system factors', such as promotions policies and research funding, can influence scientific production. On the basis of a panel of individual researchers from the biomedical and hard sciences at the Katholieke Universiteit Leuven in Belgium, Kelchtermans and Veugelers apply a quintile regression approach to counting data to assess whether productivity drivers have different effects for people performing differently. They find that factors such as promotion and access to research resources have more impact at the bottom of the distribution, that is, for less brilliant scientists. These results provide clear evidence of the need to move away from approaches based on average estimations (hence the article subtitle, 'The average scientist does not exist'). Research policies should be fine-tuned to the various levels of the distribution and should provide greater incentives at the bottom end of the distribution as the returns from funding are larger at the lower quintiles.

Industrial Economics and Science

The tools of industrial economics have been applied with some success in the quest for an effective organization of scientific undertakings. This line of investigation has opened up a number of questions about the existence of economics of scale and scope in fostering the productivity of scientists (Carayol and Matt 2004a, 2004b; Carayol 2007). In this context, much attention has been paid to the effects of size and specialization on the selection, identification and exploitation of new stars (Zucker and Darby

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1996; Schiffauerova and Beaudry 2011). The effects of their distribution in a few centres of excellence or their dissemination as a source of scientific fertilization have been investigated (Bonaccorsi and Daraio 2007). The advantages and limitations of specialization in research activities, as opposed to the traditional joint production of research and teaching, have been questioned (Goldfarb et al. 2009).

Science and Regional Economics

Several contributions based on typical regional economics notions have explored the effects of external economies both in the generation of science (research) and in the exploitation of scientific knowledge from business firms. In research, the fundamental role of external knowledge is generally confirmed. Empirical evidence suggests that spatial proximity is an important enabling factor because it facilitates market transactions that could not take place without repeated interactions, exchange of tacit knowledge and mutual trust. Several empirical investigations have suggested that regional proximity among scientific institutions increases scientific production (Antonelli et al. 2010) and clustering also occurs in regional spaces occupied by scientific institutions and in the context of research by firms (Audretsch and Feldman 1996). Other contributions cast some doubt on the actual role of proximity within clusters or stress the effects of proximity in terms of more effective transactions in the markets for knowledge (Audretsch and Stephan 1996).

In the context of the exploitation of technological knowledge, investigations into the extent to which knowledge externalities matter shed light on aspects related to the role of spatial proximity, such as the effects on the entrepreneurial activities of a local system (Zucker et al. 1998b). Zucker, Darby and Armstrong (Zucker et al. 1998a), using detailed data on biotechnology in California, stress the positive role of the proximity of particular star scientists as opposed to generic knowledge. Their results suggest that the positive impact of the research conducted within universities on co-localized firms is the result of transactions between star academics and firms rather than knowledge spillovers. The interactions between firms and academics promote knowledge spillovers, however: stars that collaborate with or are employed by firms, or scientists with patented inventions, have significantly higher citation rates than unconnected academic stars.

Property Rights on the Outcomes of Research

The issue of appropriability of the products and by-products of scientific research has been the subject of intense speculation since the early 1990s.

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An initial vibrant debate was based on two articles published in *Science* in 1992 and 1998 by law professors Rebecca Eisenberg and Michael Heller (Eisenberg 1992; Heller and Eisenberg 1998). The historical antecedent to these papers was the flurry of patent applications for genes and genetically modified organisms that were filed in those years, from a new breed of entrepreneurial biotechnology laboratories based in universities and private firms. The US National Institutes of Health and several American universities had increased their patenting activity following the Bayh-Dole Act of 1980 and the broadening of the list of patentable items (for example genetically modified organisms, including mammals). Heller and Eisenberg (1998) maintain that, on the one side, private property on scientific results was meant to sustain private investment in technology development, but that, on the other side, protecting a research tool, a gene or some other basic achievement that will become an input for other research is likely to raise the downstream costs of these investigations. At the same time, too many property rights would increase the cost of the negotiations among the parties holding the rights on complementary pieces of knowledge, a situation known as the 'anticommons effect'. A socially optimal solution involves a separation of the roles of public and private research and their related rights to claim exclusivity (Aghion et al. 2008). Scholarly works analysed the potential effects of the anticommons at three different levels: (a) the outputs of individual researchers; (b) the rules governing the functioning of the scientific community; and (c) the institutional missions of universities and their governance. Several empirical assessments show that technology transfer, entrepreneurial activities and, more generally, the university third mission, do not hamper research productivity, at least for the top researchers. Some studies find that these activities are often forerunners to more prolific research. Proof of their long-run effects is still lacking, however, and very little is known about their effects on teaching. Furthermore, there is some doubt about the pace of knowledge diffusion when science is encumbered by too strong property rights (Murray and Stern 2007), and the efficiency of the institutionalization of the transfer mechanisms (Crespi et al. 2010).

Science and Higher Education

The contribution of the economics of higher education provides a useful framework to study the budget, funding and recruitment decisions of universities, which account for the largest share of global expenditure on research. Several works focus on the peculiar production functions of universities, where the quality of the customers – students and peers – contributes to determining the quality of education and research

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(Rotschild and White 1995). For example, the brightest students improve the learning capacity of all other students because they act as inputs with superior marginal productivity. This offers justification for the practice of price discrimination (scholarships) based on talent. When the resource endowments of universities are very uneven, for example because of donations (Winston 1999), the brightest students are disproportionally attracted by wealthy institutions and consequently cumulate further advantages over the other institutions. A similar mechanism may apply to faculty members, who also generate positive externalities for the research of their peers and students.

A number of studies are devoted to the analysis of university research performance. Johnes (1992) and Massy (1996) maintain that, unlike in the case of profit maximizing institutions, a clear set of objectives is generally difficult to identify. Also, the government–university relationship is often characterized by principal–agent conflicts because universities' productivity is different from the productivity demanded by government. Johnes (1992) considers the incidence of drop-out by students, degree pass rates, and the quantity and quality of the research produced by academic staff, in order to assess universities' contributions to social welfare.

Technological Change and Science

It is only recently that typical notions of the economics of innovation have been applied to analyses of the development of science. Considerable attention has been paid to the effects of the diffusion of new technologies on the performance of scientific institutions, in terms of changes in their supply and conduct. So far little work has been done on the effects of the introduction of new technologies on the performance of research activities. Agrawal and Goldfarb (2008) studied the consequences of the adoption of the new information and communication technologies in the US academic system. Their results suggest that the adoption of Bitnet increased research collaboration among US universities, although unevenly. Middle-tier universities seem to have been the primary beneficiaries, with collaborations with top-tier institutions greatly increased; however, the reverse does not apply. Co-localized pairs experienced the largest effects in magnitude. Winkler, Levin and Stephan (2010) study the effects on research productivity of the adoption of Bitnet, the Domain Name System, JSTOR (journal storage) and other electronic library resources. The results provide support for the hypothesis that information technology improves the careers of faculty, especially at lower-tier (as opposed to high-tier) institutions. Further support for this view is produced by Ding et al. (forthcoming).

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The Mechanism Design of Research Organizations

The idea behind mechanism design is the analysis of institutions as mechanisms that produce desirable outcomes, under the assumption that agents have private information and are self-interested. The application of mechanism design to analysis of the organization of the research system, as distinct from individual research institutions, is a fast-growing area of investigation. The organization of the research system has undergone significant changes in the first years of the twenty-first century. The separation between research activities conducted in academic and public institutions and research activities performed in corporations has reduced. In-house corporate research and development (R&D) is being substituted progressively by market transactions and outsourcing to knowledge suppliers, including high-technology entrepreneurial ventures and universities. Knowledge is traded in the form of intellectual property rights or under research contracts. This emerging organization of research enables a more efficient exploitation of the intrinsic economies of scope between research and teaching that characterize academic institutions. For example, universities can make good use of older, less research productive scientists, in teaching activities; corporations find it more difficult to use their older research personnel productively (Antonelli 2008). University–industry relationships are the subject of a large body of work enquiring into the determinants and the effects of these relationships for both parties and the efficiency of the institutions and contracts under which transactions are organized. Several extensive reviews of this work are available.

A second sub-stream of research in this area relates to the allocation and efficient use of resources at the level of institutions (universities, research centres), departments and individual research units, and scientists. Adams and Griliches (1998) used data from 40 American universities for 1981–1989 to enquire into the impact of R&D expenditure on research output. They show that costs per paper are nearly the same among the top ten and the lower-positioned universities, while costs per citation are 30 per cent lower among the top universities. Private universities spend more per paper and less per citation than do state-owned universities. Aghion et al. (2010) show statistical correlations between the productivity of universities (measured by patents), their level of autonomy, and the extent to which they compete for funding. The work of Adams and Clemmons (2011) develops the analysis of research productivity in US universities focusing on intra- and inter-university knowledge-flows and interdisciplinary knowledge-flows. They find evidence that external flows – from other universities – have increased compared to internal flows – from the same university. Average interdisciplinary flows have increased less

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than intradisciplinary flows, although in engineering and mathematics, intradisciplinary flows have increased substantially.

Science and Economic Growth

While there is general consensus that scientific knowledge is at the basis of economic growth and much work has been focused on assessing the effects of new technological knowledge, very little empirical work has been done on the effects of new knowledge on growth. Since the path-breaking contribution by Jaffe (1989) there have been few efforts in this direction. However, Jaffe's work provides only indirect evidence about the positive effects of science on growth. His empirical study confirms that academic research affects the efficiency and level of the research activities conducted by firms. He finds a significant effect of university research on corporate patents, particularly in the areas of drugs, medical technology, electronics, optics and nuclear technology. In addition, he finds that university research appears to have an indirect effect on local innovation by fostering the R&D activities of the firms located in the proximity of a university. A more direct exploration of the effects of academic research on economic growth is provided by Adams (1990). He uses measures of science rather than technology to study the effect of new scientific knowledge on economic growth and develops new indicators of accumulated academic science. His empirical evidence suggests that new scientific knowledge exerts a major effect on total factor productivity. The impact of this strong causal relationship shows a lag of roughly 20 years from the emergence of a new field of research in the academic community to a boost in economic productivity. A completely different approach is taken by Mansfield (1991). He focuses on a sample of 76 US firms from seven industries and estimates the benefits of recent academic research (published not earlier than 15 years prior to the innovation being considered) on company innovation. He finds that 11 per cent of new products and 9 per cent of new processes would have experienced significant delay in their development in the absence of academic research. He estimates also that for firms, an absence of academic research would have reduced sales of new products by about 2.1 per cent and sales from new processes by some 1.6 per cent. In a follow-up study Mansfield (1998) finds even higher returns from academic research.

Adams and Clemmons (2008) assess the effects of the flows of scientific papers on industries and fields and implement a representation of the structure of basic research flows in a modern, science-intensive economy. They show that basic research flows are large within petrochemicals, drugs, software and telecommunications. Scientific knowledge generated

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in the domains of chemistry, physics and engineering spreads throughout all industries, while biology and medicine knowledge is concentrated in petrochemicals and drugs. The effects of the advances in computer science are restricted to software and communications. In general, basic research flows are concentrated more within scientific fields than within industries. Adams and Clemmons's findings indicate that there is a strong elasticity between changes in the production of scientific papers and changes in industrial output.

EMERGING ISSUES: BUILDING A SCIENCE OF SCIENCE POLICY

In this chapter we have shown that science and the organization of scientific activities were divorced from economic debate until the early 1960s. Starting in the mid-1980s, considerable progress was made to support the proper functioning of the job market for science and to set efficient property rights regimes for research artefacts. The knowledge and instruments that have been developed in recent years have paved the way for the substantial contribution of economics to support political and social decision-making in relation to scientific progress, including decisions on the most efficient funding, institutional settings and resource allocation. We conclude this chapter by suggesting some directions for future investigations. We highlight possible future developments in the science of science policy, in terms of perspectives of inquiry, topics worthy of investigation and methodological tools.

In terms of perspectives of inquiry, in the early contributions to the economics of science the focus tended to be on individual researchers as the main objects of analysis. The organization of science at the institutional level, in both the private and public domains, was seen as being less important. There have been even fewer studies of the interplay between the single individual and her own set of motivations and rewards, and the institution (department, the school, or central administration) to which the individual belongs. A classical principal–agent framework would offer a simple, not yet exploited, starting point for future investigations.

In terms of the future direction of inquiry, we can pick out three. First, the contribution of science to innovation and ultimately to economic growth is generally misunderstood. As the above review shows, a few important works have been published, but much work remains to be done in order that answers can be found to some fundamental questions. Second, with regard to the effect of proximity and spatial effects, few

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investigations have been dedicated to assessing the possible existence of negative externalities. For example, it is not clear whether the concentration of homogeneous research activities differs from the concentration of heterogeneous ones. In this respect, a clear, distinct appreciation of the effects of Jacobs (scope) and MAR (scale) externalities in science would constitute a promising direction for further investigation. While the effects of technical externalities and the consequences of agglomeration and personal interactions on knowledge-sharing processes have received attention, little work has investigated the effects of spatial proximity in terms of pecuniary externalities. Third, much recent work ignores the central issue of determining the efficient amount of resources that a system should invest in the generation and dissemination of knowledge and the problems related to identifying the fields in which these resources should be invested. Clearly, such an analysis would be complex given the uncertainty associated with research activities, but progress could be made. For example, it is becoming clear that an analytical framework is needed that is able to articulate the need for interactions between the academic system and the business community, both before and after the generation of knowledge. Some analyses considered the dissemination of knowledge, once generated, but failed to pay attention to the crucial identification of the fields of knowledge where resources should be invested and the level of investment in these various areas. Relying on the basic methodology of mechanism design, scholars can advance this work. It is clear that in a homogeneous, Hayekian system the alignment of incentives among profit-seeking agents is (expected to be) able to address the issue. If universities are state funded, with no incentives for the successful identification of new profitable knowledge fields, how will they direct their activities? How will new fields of activity be chosen if expected profit cannot be forecast? The emergence of knowledge outsourcing might be appreciated as the product of a spontaneous order (implemented by design?) that enables not only better dissemination of the knowledge generated, but also better allocation of the resources required for the generation of new knowledge.

A viable starting point may be to work out models for trajectories in science and research. Some of the existing work identifies two main processes that explain the development of research trajectories. First, some trajectories are chosen deliberately, based on the technical and cognitive capacity of the investigators and on their expectations of potential returns. Second, research can be organized as a problem-solving activity, where the problem to be solved can come from industry, from government (space mission, defence projects), or from the scientific enterprise (for example big science projects, scientific tools). A considerable proportion

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of both types of research is fairly predictable in terms of the probabilities of success.

Finally, in terms of the tools of analysis, there is a need to move beyond the consolidated set of bibliometric techniques developed in the 1960s comprising metrics of productivity (based on counts of articles) and impact (based on counts of citations). These measures, although useful, fail to take account of countless other features of scientific productivity and constrain the spectrum of the inquiry (Garfield 2005). Additional indicators have been proposed and studied within bibliometrics, but their use in economic inquiry remains quite limited and needs further development and testing by statistical economists. For example, backward citation analysis can be used to construct measures of scope and interdisciplinarity, similarly to what has been done in the case of patents, and content analysis can be used to map subfield coverage and evolution.

NOTE

1. A shorter version of this chapter is forthcoming as the editors' introduction to a Special Issue of *Industrial and Corporate Change* (2011).

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