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Science, innovation, and public services: editorial introduction

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ABSTRACT
The quality of public services is critically influenced by innovation and, ultimately, by advances in basic research, which however embeds the feature of a global public good. Two broad issues emerge. The first concerns the evaluation of the socio-economic impact of science. What are the benefits and spillovers that R&D investments, research infrastructures and big science can bring to society? The second concerns which type of institutions and policies are most suitable for supporting R&D activities. These topics discussed in this article represent the core of the special issue "Innovation and Public Services: from the lab to enterprises and citizens"

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Policy Highlights

(1) In case of basic science, the government is called not just to provide a public good, but to invest in the production of an unknown good, whose future benefits and applications are largely unknown.
(2) The role of government in facilitating the creation and transition of knowledge from the lab to wellbeing is a crucial one;
(3) Governments should ensure freedom in the process of knowledge creation and diffusion, and avoid manipulating the internal logic of science
(4) When public funding is required, the developments of large-scale research infrastructures should be complemented by a socio-economic cost-benefit analysis

1. Introduction

When one thinks of a particle physics laboratory, what comes in mind is the secluded world of scientists and of their experiments, with big and costly accelerators. The most powerful one is the Large Hadron Collider at CERN, hosted in a 27 Km circular tunnel, one hundred meters underground, between Switzerland and France (Amaldi 2015). But what are the benefits of making particles colliding and re-creating particles which

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existed billions of years ago for the common citizen, who probably doesn't know what a Higgs boson is and the importance of its discovery in explaining the origins of the Universe? Is there an impact of science on R&D and innovation in public services in such fields as energy, telecoms, transport, environment, and health? What role should governments play to support the journey of knowledge from laboratories to the needs of society? This special issue of the *Journal of Economic Policy Reform* contributes to answering these broad questions by providing examples from different fields.

Well performing, high quality, accessible and affordable public services, or services of general interest in EU legislation (SGI), represent a priority in the national and supranational policy agendas (Florio 2013; Clifton, Díaz-Fuentes, and Fernández-Gutiérrez 2016). SGI are critically influenced by sustained innovation, as both firms' productivity and consumers' welfare depend upon new knowledge embodied in the services sector. Advanced health technologies, digital devices for telecoms and transport sustainability or smart infrastructures for energy efficiency and decarbonisation represent some relevant examples. These innovations would not be possible without basic research, discoveries in laboratory, and subsequent applied R&D. Governments, regulators, development agencies and state-owned enterprises can play a critical role in supporting basic research and innovation, as market failures hinder the process of knowledge creation, bringing to a sub-optimal level of private investments. Basic knowledge embeds the feature of a global public good, and market players might be reluctant to enter this activity, with the risk of discovering something with unknown use or with a limited appropriability of its related benefits. Optimal investments in innovation are also undermined by the intrinsic risky nature of R&D. R&D is not always successful and, even when it leads to positive and patentable outcomes, the related economic returns remain uncertain and deferred in time. These arguments are supported by empirical evidence on how the processes of market liberalisation and privatisation have negatively affected R&D intensity and investments in innovation (Munari, Federico and Sobrero 2003; Jamasb and Pollitt 2008, 2011, 2015; Sterlacchini 2012; Chuanyin 2012), particularly in the case of privatisation through leveraged buyout (Zahra and Fescina 1991; Long and Ravenscraft 1993).

Governments may play an active role by directly supporting research infrastructures and R&D, through development banks and public enterprises with ambitious missions (Luc 2014; Belloc 2014; Tonurist and Karo 2016; Frigerio, Clò and Vandone 2019), or indirectly by means of their SGI, and regional and innovation policies (Alessandro, Reid, and Leon 2015). From this perspective, two broad topics are investigated in this special issue. The first concerns which type of institutions and policies are most suitable for developing and supporting R&D activities. *How should governments address their policies to support the flow of new knowledge from research laboratories to enterprises and citizens?* The second concerns the evaluation of the socio-economic impact of science. *What are the benefits and spillovers that R&D investments, research infrastructures and big science can bring to society as a whole*?

In the following section we introduce a general discussion and conceptualisation of the topic, then we move to examples, and finally suggest some economic policy implications.

2. A double track of knowledge creation

According to Foray (2004), the core mechanisms of knowledge creation are discovery and invention. Discovery reveals how nature works. It assumes that something that we are not aware of in the first place exists. Science conveys information to us through its special language. Invention, instead, builds on such knowledge to create new objects and processes, not previously existing in nature.

The social loci of these knowledge creation mechanisms have evolved over time with their own specific features. To simplify a complex story, here we shall refer to laboratories for basic research on one hand, and to R&D units for profitable innovations on the other hand.

The typical hosting organization of R&D units are firms that are often owned by private investors who are motivated by profit seeking. Although innovation is a crucial engine for firms' productivity, and ultimately economic growth, private investments in innovation tend to be sub-optimal due to the intrinsically risky nature of R&D activity. R&D is not always successful and, even when it leads to positive and patentable outcomes, the related economic returns remain uncertain and deferred in time. Governments have traditionally supported corporate R&D units in their role of knowledge creators. Examples of government interventions to support R&D include subsidies to private firms aimed at overcoming a risk-adverse attitude towards an uncertain activity (Busom 2000; Salter and Martin 2001; Trajtenberg 2002) and intellectual property protection (Scotchmer 1991; Landes and Posner 2003; Lemley 2004). Patents grant a (temporary) monopolistic protection of the intellectual ownership of the invention. Without any legal protection against copying or any legal capacity to recoup the costs of creation and distribution, competition would bring the price of invention down to the marginal costs of copying and firms would not be willing to invest in R&D in the first place. IP protection is therefore primarily aimed at creating incentives to invent and innovate, as it gives firms the exclusive rights to reproduce and distribute their inventions, thus granting them the rewards they otherwise could not obtain.

As opposed to the case of R&D activity, which leads to innovative and patentable products, private entities are reluctant to invest in basic research. Indeed, discoveries resulting from basic research share the features of a global public good and are rarely patentable. Moreover, at least in the short run, their potential practical applications remain largely unknown, so the related monetary benefits resulting from investments are limited and cannot be fully appropriated by the investing agents. For this reason, laboratories for basic research have been traditionally hosted by universities or other institutions whose objectives depart from a short-term profit maximisation goal. Moreover, in the last decades, many governments have supported large-scale, often international, research infrastructures (RIs), like CERN, the International Space Station, the Human Genome Project, the European Molecular Biology Laboratory, the European Space Agency and many others. These RIs are entirely focused on single discovery missions and emerged from the scientific need to overcome existing universities' and firms' research models, as both organisations seem increasingly unable to cope with the scale of contemporary scientific agendas. In a sense, a university is the managing body of a portfolio of intellectual projects. It has to accommodate the research and educational objectives of various scientific communities. As they have very long-term objectives (Bologna and Oxford have now reached their tenth century of continued activity), risk mitigation strategies lead them to diversify their knowledge investments in a plurality of fields. However, nowadays, diversification or risk-adverse attitudes hardly match with contemporary scientific goals. The progress of our understanding of nature in past centuries, since Galileo's times – to mention a conventional breakthrough- is such that the investment needed for new discoveries is large, the operation cost high, and the return often very uncertain. Just to make an example, the University of California needed to create an entirely separate organisation to manage the Lawrence Berkeley National Laboratory (LBNL) on behalf of its funder, the Office of Science, US Department of Energy. The LBNL hosts 3,200 scientists and engineers,[1] and CERN experiments host more than 2,000 PhD students and post-docs at any time. For most universities, it would be difficult to accommodate such large-scale RIs in their own budget, hence they now tend to collaborate in international consortia that own the laboratories and share them among participating institutes, and in some cases also provide access to third parties.

Moreover, firms usually cannot create such large-scale scientific laboratories because they focus on a portfolio of potentially profitable investments and cannot deal with the increasingly open model of science with its diluted ownership. There are exceptions, such as EDF (Electricité de France), the former electricity supply monopolist with around 2,000 R&D staff, or the AT&T[2] Bell Laboratories before the liberalisation of the telecommunications market in the US. Some private investors may support charities out of the profits of firms, such as the Bill & Melinda Gates Foundation (https://www.gatesfoundation.org). Charities, in turn, may support research, but this is usually a funding arrangement and does not lead to the creation of dedicated scientific organisations.

What emerges from this broad picture is the different role played by public and private institutions in the process of knowledge creation. Economic organisations see inventions as a side-product of their development strategy or as tools aimed at creating economic value for their owners. This is not the case of universities, scientific societies, royal academies of the past, and contemporary RIs that typically seek knowledge *per se*. According to this established view, governments play a crucial role in correcting market failures linked to the public good's nature of knowledge, which leads to a sub-optimal level of investments in innovation.

This is why taxpayers' money is expected to support laboratories, R&D subsidies, or why society as a whole is willing to bear a deadweight loss associated to the temporary monopolistic position granted by intellectual property rights.

This conceptual model, which belongs to the public economics' traditional doctrine of government intervention as a remedy to market failures (Atkinson and Stiglitz 1980), while not necessarily wrong, is incomplete for several reasons. First, it tends to ignore that, by definition, knowledge before discovery doesn't exist. Thus, it is not clear what the optimal amount of knowledge before it is created would be. Second, we don't even know how exactly to measure useful knowledge *ex post*. Third, the necessary research arrangements for discovery and invention are different, or in other words, knowledge is not a homogeneous good and its demand comes from different agents. In the present introduction, we briefly elaborate these three issues, and we discuss why the "market failure" view about the role of publicly funded research may be flawed. A different view may be proposed by drawing on the concept of "market creation" (Mazzucato 2016; Mazzucato and Penna 2016), but also by going beyond the market paradigm itself to a certain extent. Our conceptualisation of the relation between the laboratory and the R&D unit has interesting policy implications, particularly for the provision of certain public services, that will be discussed at the end of this article.

Starting from the seminal model by Solow (1957), growth is driven by capital accumulation, labour growth and change in total factor productivity, such as that in a Cobb–Douglas production function with a single output (Y) produced by labour (L) and capital (C):

$$Y = C^{\alpha}(AL)^{1-\alpha} \tag{1}$$

where $0 < \alpha < 1$ is the output elasticity with respect to capital. A refers to labour-augmenting technology or exogenous "knowledge". In contrast, in the «Endogenous Growth Theory» that dates back to Arrow (1962), Lucas (1990) and Romer (1986), investments in human capital, innovation, and knowledge are determinants of growth. In this case, positive externalities of knowledge would counterbalance the capital's decreasing returns. Technological or knowledge spillovers were explicitly modeled by Griliches (1979) where the firm's output depends on its own knowledge investment but also on the knowledge of other firms[3]. The Griliches model of within-industry spillovers is captured by a Cobb-Douglas production function:

$$Y_i = BX_i^{1-\gamma}K_i^{\gamma}K_a^{\mu} \tag{2}$$

where B is a constant and Y_i is the output of firm i, which depends on the level of conventional *inputs* X_i, its specific knowledge *capital* K_i, and the aggregate knowledge in the industry K_a[4]. The coefficients $(1 - \gamma)$, γ and μ represent the elasticities of output with respect to internal and external R&D capital respectively.

Such knowledge spillovers can be generated either by other private firms operating in the same (or in a linked) industry, or by the public sector through organisations like RIs, agencies, public research universities and State-owned enterprises. Therefore, the model simply aggregates knowledge in the industry as the sum of all firm-level knowledge ($K_a = \Sigma_i K_i$), assuming there is an optimal allocation of resources and all firms face the same relative factor prices. Therefore, aggregating all the individual production functions yields the following equation:

$$\sum_i Y_i = B\sum_i X_i^{1-\gamma}K_a^{\mu+\gamma} \tag{3}$$

Hence the aggregate production function has a higher coefficient of aggregate knowledge capital $(\mu + \gamma)$ than the coefficient at the individual level (γ) because, along with private returns, the aggregate production function incorporates R&D spillovers. Policies supporting R&D and innovation will then be able to promote growth in the long run and counteract the externality arising from the spillover of knowledge from one firm/organisation to another one.

While this model may represent mutual spillovers between firms and industries, it is not very helpful in capturing the relation between discovery and invention. The peculiarity of discovery is that the demand for new knowledge is driven by scientists who are often, simultaneously, users and producers of the knowledge output, which typically consists in publications. This demand is unrelated with the demand of productive knowledge by R&D units within firms. "Publish or perish" may be the rule for scientists, but "profit or perish" is the rule for investors.

Hence, in principle the previous model should be augmented by a "productive science" term, a S factor, such that:

$$\sum_i Y_i = B\left(\sum_i X_i{}^{1-\gamma} K_a{}^{\mu+\gamma}\right) S^\sigma \tag{4}$$

where σ represents factor-specific elasticity.

This conceptual model raises some new research questions concerning the relation between productive science and R&D firms units and, ultimately, final citizens and social well-being in general.

How do discoveries in labs and the creation of firms' inventions intersect? What brings the knowledge created by the Human Genome Project, entirely funded by government grants, to scientific laboratories, to the R&D units of pharmaceutical firms and ultimately to a new drug? How are the technologies developed at CERN to accelerate protons eventually embodied in machines to cure cancer? Mazzucato (2013) presents several good examples of the interplay between government funded research and corporate R&D. But how does such an interplay actually work, and to what extent does it fully develop the potential enhancement of the social impact of knowledge creation? This interplay was noticed many years ago: Marx and Schumpeter's analysis of capitalism placed knowledge creation and its appropriability by entrepreneurs and investors at the center of their theories of economic change. For decades, formal R&D or informal processes of experimentation have been explored in detail by the flourishing field of "economics of innovation". What has perhaps been less explored, beyond narratives and case studies, is how synergies between different institutions, such as research institutes, state-owned enterprises, private firms, and regulators, with different objectives, funding, and ownership arrangements arise.

One may also wonder what the optimal level of productive science, deriving from an evaluation of related costs and benefits, truly is. The conceptual and empirical problem here is that nobody knows *ex-ante* what *productive* science will be, the S term in (4) as only a part of it will be applicable with any computable probability. As a result, the metric of S would be undefined: government expenditures for basic research *per se* do not reveal whether and when discoveries will have an impact on social well-being. Hence the σ would also empirically difficult to estimate. We are aware, with the benefit of hindsight, that after some time the discovery of the electron lead to inventions that have dramatically changed the technology we use to manufacture goods, communicate, store and compute data, and so on. But can we say the same for the discovery of the Higgs boson now? Perhaps in the XXII century somebody will have an answer to this, but public investment in the LHC had to be justified more than twenty years before a discovery took place. Thus the "market failure" is in fact deeper than the endogenous growth frame implies. Government intervention is not just about filling a gap in the production of a known good, but rather about taking the risk of investing taxpayers' money in the exploration of something totally unknown *ex ante*, perhaps with no use for very long time.

Determining the chain through which discoveries are embedded into firms' inventions and, ultimately, improve our daily life, and assessing the socio-economic benefits associated to basic research are not easy tasks. One could argue that such a comprehensive assessment is impossible to develop and that the criteria adopted to grant public financial support to basic research should go beyond a cost-benefit analysis approach. However, recent empirical research on the social benefits and costs of large scale research infrastructures (Florio, Forte, and Sirtori 2016) present a surprising result: investment in basic research may pay itself back even when one doesn't consider the unknown and totally uncertain future benefits of discovery. There are four types of particularly important impact pathways that are: human capital effects for the PhD students and early stage researchers who are involved in laboratories, learning effects for firms under procurement contracts, dissemination of free software and data, specific and generic cultural effects. These were identified several years ago by Salter and Martin (2001) and their measurement in an applied welfare economics model has been recently proposed by Massimo (2019).

In the case of the Large Hadron Collider, Florio, Forte, and Sirtori (2016) find that the social value of such cumulative benefits up until 2025 is such that the benefit/cost ratio is in excess by 1.20. Similar results are reported for expected economic returns on other RI projects that are funded by the European cohesion policy (Florio, Morretta and Willak, 2018).

Thus, it seems that investment in discovery can be evaluated and predicted in terms of its social welfare side-effects (i.e. beyond scientific knowledge creation) on human capital, procurement for innovation, release of software and data, services to users, opportunity cost of publications, and direct and generic cultural effects. In other words, one can break down the social impact of what laboratories do in terms of welfare effects on social groups (firms, students, scientists, certain types of users, and the general public) and design ways to enhance beneficial impacts such as mechanisms that increase the probability of a transition from the laboratory to inventions, and eventually trickle down to social well-being through innovations in the supply of consumption goods and public services.

In this social welfare perspective, we present and comment on some of the contributions in this special issue below.

3. Perceptions of science as a public good

Little is known about the social attitudes of citizens in relation to basic research. However, as taxpayers are the ultimate funders of basic research, it would be important to know whether they are willing to pay in principle an what they actually implicitly pay for through their taxes. In this special issue, drawing from a wide empirical literature in environmental economics, Catalano et al. (2018) report a contingent valuation experiment on the willingness to pay for research with the Large Hadron Collider at CERN, with more than 1,000 students from five European universities (in France, Italy, Spain, UK). Respondents were sampled from a large variety of different curricula, including the humanities, social sciences, and hard sciences. Younger students show a higher willingness to pay. Among sources of information about the LHC, on-line news and TV programmes are the most quoted by the interviewees. No significant gender and family composition differences exist on the WTP; in contrast, knowing what a particle accelerator is, having heard about the LHC and the Higgs Boson and declaring that fundamental research is important to some extent, increase the probability of a "*yes*" response. Certain university degrees, such as those in the humanities and social sciences, display negative coefficients compared to scientific degrees. However, the type of university degree does not discriminate between paying and not paying. The latter is probably the most important finding, as it suggests that even citizens with no personal interest in starting a career in science-related jobs, support the funding of science.

This result has very recently been confirmed by Massimo (2019) by means of a survey to a representative sample of 1,005 French taxpayers (France, along with Switzerland, is one of the hosting states of CERN). They found that a slight majority of the respondents agree to pay an additional tax for a future particle accelerator at CERN, that the probability of a positive answer is conditional to both income and previous awareness of what CERN does, and that the estimated average willingness to pay for a set of individual control variables is significantly higher than the current implicit tax burden that is part of the yearly funding of CERN by the French government.

The message arising from these contingent valuation experiments is that citizens are, to a certain extent, aware that research performed in the main science laboratories has a potential impact on their lives, and in any case that it is worth it to carry on even in fields, like particle physics, that are very distant from the respondents' day-by-day experience. In this perspective, there is a public good dimension of science, and research infrastructures are providing a new form of cultural public service, as they meet the citizens' demand for such public good.

4. From space to earth: the benefits of copernicus satellites for economic policy

In this special issue, Tassa (2019) presents an important case study about the potential benefits – but also the challenges – related to the transition from science to economic innovation: Earth Observation (EO) through Sentinels, a system of satellites managed by the Copernicus program of the European Space Agency (ESA). When the program will be completed there will be a full array of Sentinels, each based on advanced technologies such as special types of radar, multispectral optical, infrared, spectrometry. These technologies are the result of research in several laboratories, some of them initially for military purposes, but under Copernicus exclusively for civilian use. The Sentinels can monitor a very large set of observation targets: sea ice, oil spills, marine winds, land deformation (such as after earthquakes), agricultural territory and forests, coastal and inland waters. This free availability to all citizens, public institutions and economic organisations can have a tremendous impact on our daily life. Policy making can benefit from the application of these data, ranging from the accurate monitoring of natural events, disaster prevention, emergency management, to the detection of illegal behavior. All data are released for free, and in most cases even without the need to register. While the cumulated number of registered users have been in excess by 110,000 up until 2016, and it is estimated that over 500 firms and a number of public sector agencies regularly access the data to embody them in the services they offer, little is known about the socio-economic value of the data's benefits. Tassa proposes a sensible analytical sequence to track the "value chain" of EO data: from EO sensor raw data to EO data products, to value-added service, and finally to the socio-economic value of EO-based information. She also mentions pilot case studies that have adopted this approach, for instance to estimate the benefit of data on sea ice for winter navigation in Finland, starting from benefits to ships and ports and leading to the storage cost savings of retail distribution thanks to a more regular supply of goods.

In our perspective, there was fundamental inefficiency in earlier EO research related to the gap between the wide opportunities offered by the free availability of the data and their actual use. According to Tassa (2019) initially the pioneering applications of EO were developed and refined mostly within a relatively restricted community of scientists and specialists. But the true challenge was how to spread the applications with a potential socio-economic impact.

Only when a political strategic decision was made at an EU level with the Lisbon Treaty (2007) to create a European Space Policy, and more recently with the inclusion of Copernicus in the EU regular budget (2014), was there a change of pace and actual use growth was sustained.

This example clearly shows one of the most important points in the discussion in the previous section: while in some cases there may be informal mechanisms ensuring permeability between science and R&D for its application to public services, only a mission-oriented public policy can bridge the gap between the two worlds. There is no automatic spillover.

5. Energy innovations

The contribution by Sterlacchini (2019) discusses the role played by public policies in supporting innovation in the energy sector. Being one of the most critical and regulated sectors of our economies, and in light of the fundamental role of this service, which is of general interest for our well-being, it is interesting to understand to what extent innovation is correlated respectively to policy and economic drivers. Sterlacchini lists an impressive array of climate change mitigating technologies related to energy generation, transmission, and distribution. These include *inter alia*: wind, solar, geothermal, marine, and hydro energy; biofuels and fuel from waste; energy efficiency technologies; nuclear fusion and fission reactors; superconducting cables for electricity transmission; new kinds of batteries; thermal storage and other forms of energy storage; and smart grids, just to mention some fields. Fundamental research is still needed to understand the principles of scientific breakthrough which may allow a transition to different energy models. While in some cases firms' R&D is motivated by profit opportunities, in other cases, firms are scarcely interested in promoting innovations which would negatively affect their business opportunities: for instance, in most cases energy efficiency would simply result in a reduction of energy consumption, and this cannot be a primary R&D target for firms whose core business is power generation and energy sales.

In this context, to what extent does corporate R&D respond to market signals? And which role can public policies play to promote innovation in this field? Sterlacchini uses oil price as a proxy for market incentives, while energy-related patent applications in 19 OECD countries proxy innovation in this sector. Then he introduces alternative indicators of environmental policy stringency both at national and global levels to study the correlation between the share of energy patents in the total number of filed patents and variables of interest. In his words, the main findings are as follows:

"We find that the stringency of environmental policies has exerted an impact on energy patents that are greater and more significant than that of oil prices. However, this emerges when the aggregate index of policy stringency (averaged among OCED countries) is applied."

This result reinforces our view that market mechanisms (oil price) alone are not sufficient to drive the process that goes from science to innovation, or even to support R&D itself. Public policy is key, but possibly at a global, rather than at a national, level. After all, climate change is a global concern, and core players in the energy industry are represented by multinational firms. Therefore, in the models presented in Section 2, a policy factor should be included in the production function, with an effect that is mediated by science and R&D, as empirically developed by Sterlacchini in his paper.

6. Water management innovations

McDonald (2018)makes the important point that in some public services the innovation of governance is as important as technological change. He mentions the following areas of the latter: improvements in water treatment, detection of leaks, repairs of the hydric network, nutrient recovery, energy saving, use of new piping materials, water recycling and desalination. Perhaps the most important technological change in water services, as in other public services, is related to information with smart metering and web-based digital mapping. It also seems that artificial intelligence has the potential to transform the water industry.

However, according to the author, these can be classified as incremental innovations rather than actual breakthroughs. On top of that, social innovation in the water industry's governance mechanisms represents a critical challenge, and in this area government-owned operators seem more open to change than their private counterparts. Cases of co-production, de-commodification and public-public partnerships are discussed as major social innovation challenges. These changes in the governance and management of the water industry are seen as preparatory towards a transition from a purely "technical" hydrological cycle to a "hydrosocial" cycle model.

In our perspective, social innovation, technological innovation, and scientific research are potentially interlinked and part of a new mission-oriented policy. For example, it would be inefficient to invest in research on real-time computerised water leaks detectors with new advanced technologies in the absence of any measure aimed at saving water in the downstream sector and at preventing its waste by users who are not involved in environmental objectives. As mentioned in one of the previous sections, earth observation satellites may now offer extremely precise information on changes in water availability. But this information is helpful only if local governments, water companies, and ultimately citizens, are able to take advantage of such advanced technologies to manage water as an essential good, beyond the inadequate signals that are provided by price mechanisms in a sector where privatisation, when tested, was found to be inefficient.

7. Regulation, behaviour and innovation

An important question raised by Trillas (2019) regards the risk in network industries, such as energy and telecommunications, that regulator behaviour could be affected by a number of possible deviations from rational or optimising choices. He particularly focuses on the issue of "expert bias". In past decades, the governance of various services of general interest has been managed by expert agencies, with independent regulators falling in this category. However, a consolidated finding of the behavioural economics literature is that all agents, including experts, deviate from full rationality for a number of reasons reviewed in the paper. These include: availability bias, influence by the media, scandals, political cycles or accidents; confirmation bias, which is related to prior beliefs; herd behavior; action bias, because of the risk of being criticised for delaying decisions; tunnel vision and cultural views, including the failure to adopt a broader possible interdisciplinary perspective. Social norms, such as fairness and legitimacy, may also have some influence. As some of these biases may lead to increased uncertainty and underinvestment, R&D efforts by regulated firms may be hindered by the risk of expropriation.

Even a state-invested enterprise, a company with equity that is shared among government and private investors (such as many telecommunication and energy companies in Europe nowadays), may need to minimise the risk that the long-term returns to its research investment will be expropriated by the regulator, for example by squeezing profit margins after the investment is committed because they are listed on a stock exchange. In many countries, independent regulators were created as part of privatisation and liberalisation policy packages, and have focused on competition and on containing the incumbent's market power. Their interest in long-term R&D has been limited, and they paid scant attention to its decline in regulated firms; see Sterlacchini (2012), Jamasb and Pollitt (2008, 2011, 2015). Clearly, firms' absorption capacity of radical innovation coming from the lab environment (for example superconducting cables in electricity that were initially experimented for magnets of particle accelerators) is also hindered if the regulators overemphasise one aspect of their delegated policy mission for historical reasons, or if such a mission is silent regarding R&D strategies.

8. Conclusions: further research and policy implications

There are several indications for further research and for public policy arising from this special issue and from the above discussion. In terms of theoretical and empirical analysis, it seems that the "market failure" justification for government intervention on science and R&D support doesn't fully capture the core problem. There are, of course, knowledge externalities related to research, but the standard definition of an externality is such that the relevant good should be well defined to identify the benefit or the cost to third parties. In the case of basic research, a discovery, by definition, refers to a good that is not well defined *ex-ante*, thus the usual private versus social demand and supply curves found in textbook externality cases cannot be drawn upon.

Hence, the role of the state is not just to fill the gap in the supply of a known good because of a market failure, but rather to invest in the production of an unknown good, which may or may not have a future use. This situation poses a special challenge to economic analysis. Moreover, in the perspective of policy makers, it seems difficult to justify government expenditures in fundamental research facilities to taxpayers when its returns to society are so uncertain (and there are no military justifications for them, which was the traditional argument, used particularly in the US, to support the Manhattan Project and research on nuclear weapons, but also the Apollo Lunar Program in the Cold War years).

Further research is needed to assess whether the social benefits of scientific knowledge creation are greater than their benefits, and some results suggest that this is particularly the case when one focuses on the impact of research infrastructures and science on technology, human capital, spillovers to public services, and cultural goods. As mentioned above, some new methodological approaches adopted for this purpose include social cost-benefit analysis, the analysis of cascading chains, the empirical analysis of the role of policy and regulation in promoting R&D, the study of social innovation in public services, of behavioural regulatory economics and innovation, as well as contingent valuation experiments that are carried out to elicit citizens' willingness to pay for science.

In terms of public policy, the role of government in facilitating the transition of knowledge from the lab to wellbeing is a crucial one. Science has its internal rules and priorities, based on such mechanisms as project peer reviews, consensus building in research communities, reputation of the proposers of new projects, and so on. Governments should ensure freedom in this process and avoid manipulating the internal logic of science. Governments, however, are also responsible towards citizens, who are the ultimate funders of basic research, and therefore of enhancing the process that transforms curiosity-driven projects into innovation as far as possible, leading to increased well-being. To do so, we suggest that the scientific case for a large-scale research infrastructure be complemented by a socio-economic case when public funding is required. It would be particularly helpful if this were to be done in the context of a mission-oriented innovation policy. Scientists should be invited to think to what extent what they do may directly help to address such fundamental social challenges as climate change, energy transition, health in an ageing economy, the digital economy, sustainable transport, and management of water and waste, just to mention a few. A systematic *ex ante* and *ex post* analysis of social benefits and costs of scientific projects may stimulate scientists to replicate the journey which lead Marie Curie to design the first mobile units for x-rays that were used to assist wounded French soldiers during the first world war, or Enrico Fermi to turn theoretical research on neutrons into the first nuclear reactor. What was and still is the result of the creativity and generosity of individual scientists may became a collective endeavour, mobilising scientific communities, government and – to a certain extent – citizens. Lawmakers, ministries, regulators, funding agencies, and possibly the users of public services should find ways to offer adequate incentives to scientific projects that, directly or indirectly, even if in the very long term, are most promising in the perspective of public innovation missions.

Notes

1. http://www.lbl.gov/laboratory-organization-chart/, accessed on 16 February 2018.
2. AT&T Inc. is an American multinational conglomerate holding company, headquartered in Dallas. For more on the history of the Bell Labs, see https://en.wikipedia.org/wiki/Bell_Labs.
3. See also Romer (1990), Aghion and Howitt (1992) and Grossman and Helpman (1991).
4. Both the conventional inputs X_i and the specific knowledge capital K_i are assumed to have constant returns for simplicity. If these assumptions are relaxed, the main idea continues to hold.

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