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The changing role of science in the innovation process: From Queen to Cinderella?

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ABSTRACT

An overview of how the role of science in relation to innovation has been defined over the past five decades is given, showing a change from a linear to a chain-linked model of interpretation. A third analytical grid, leading to a new model is proposed, summarizing the current research on the nature of economically useful knowledge, the diversity of intervening players in learning and the outcomes of innovation. While the chain-linked view surpassed the linear model by emphasising that science is part of the process but not necessarily the initiating step, we need today to explicitly acknowledge the multi-player dimension of innovation and the wider institutional setting where distinct forms of learning take place. The reason is simple: almost all high added value products embody elements of scientific knowledge. But science is only one of a plurality of other sources of knowledge that induce innovation-based growth. More attention should also be given to understanding markets and organisations.

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1. Introduction[1]

No single activity has had a deeper and broader impact on modern society than science. Science as culture has shaped our contemporary institutions and in western societies it has imposed a world outlook where it is assumed that in principle everything can be explained without reference to the gods. Without science we would not have experienced the consequences of the Pill, the Bomb, Voyager or the Computer. The impact of scientific progress on the economy has been equally dramatic. Almost all artefacts and services characterised by high added value embody elements of scientific knowledge. Drugs embody results from research in biology, chemistry, biochemistry and genetic engineering. Software and hardware embody advanced mathematics, physics and system engineering. Increasingly services depend on the use of advanced information technology, and on mobilising methods and insights from psychology, sociology, economics and management sciences.

In a society where money and economic growth are regarded as the most valid indicators of performance, it is tempting for advocates of science to point to the economic impact as the major argument for why the public should support science. For policymakers it is equally tempting to operate on the basis of a simple model of innovation and growth, where investment in science is seen not only as a necessary but also as a sufficient condition for innovation-based growth. It is characteristic that the

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[1] The arguments advanced in this paper were discussed at the Centre for Advanced Study, Norwegian Academy of Sciences, August 21, 2007, and at CES, University of Coimbra, November 21, 2007. We wish to thank the participants, discussants and organisers for their engagement, questions and comments. We benefited from the ideas and thoughts of many colleagues and would like to refer particularly the contributions of Jan Fagerberg, José Reis, João Ferreira, Ricardo Coelho and three anonymous referees. Earlier preliminary versions of the model underlying this paper were sketched out in a report to COTEC [1] and subsequently in a working paper format [2]. The responsibility for the arguments and limitations of this paper is ours alone.

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most salient European innovation policy measure to implement the Lisbon Agenda has been the Barcelona 2% + 1% objective for, respectively, private and public R&D to GDP ratios.

There are inherent risks in exaggerating the expectations regarding the direct impact of science on innovation and underestimating other sources of innovation such as experienced-based learning within industry [3]. Among policymakers it has resulted in disappointments and in references to what they see as 'paradoxes': domestic strength in science not being reflected in innovation-based economic growth [4]. To overcome these paradoxes policymakers look for solutions that aim at a commercialisation of science. It may result in a transformation of universities into 'patent producers' and in a problematic neglect of its most fundamental role serving industry and society with well-trained and critically minded graduates.

This paper gives a brief overview of how scholars have defined the role of science in relation to innovation moving from a linear to a chain-linked model of interpretation. We propose a third type of model — a "multi-channel interactive learning model" that summarizes current research knowledge in relation to a number of key questions, from the sources of economically useful knowledge, through diversity of the intervening players in the learning process, to the outcomes of the innovation process.[2] On this basis, we try to articulate what we see as the contribution of science in the innovation process in the current era.

The Queen–Cinderella reference in the heading refers to a double and equivocal process of change. On the one hand science may have become "more useful" than before (Cinderella-like) in the sense that its impact upon economic performance has become more generalised both on the supply and demand side. On the supply side research on marketing and management has become increasingly important for innovation. On the demand side more and more firms operating in so-called low technology sectors need to draw upon science when developing new products and processes in order to remain competitive. On the other hand science, and this is especially true for natural science, has come to lose its "royal" position as a generally recognised autonomous and dominating factor behind innovation. First, research on innovation has shown that the assumption, that investment in natural science almost automatically generates discoveries easily transformed into innovations, in most cases is wrong. Second, those in charge of science, technology and innovation policies have been slow to realise this, which led to the development of new regulations of universities that tend to make them 'the handmaids of industry'.[3]

2. The linear model

It is interesting to note that the first systematic and influential economic arguments for government support of science came from scientists and not from economists. Already in the 1930s, J. D. Bernal [7] pioneered an effort to measure R&D as a proportion of GNP in the UK and he argued that raising this ratio from 0.2% to 2.0% would have a major impact on economic growth. Immediately after the Second World War, Vannevar Bush [8] developed a similar argument in the US context in the influential report *The Endless Frontier*.

While both Adam Smith and Karl Marx recognised the important, but subtle, role of science as a source of innovation and as a productive force, it was not until the end of the 1950s that economists came up with systematic arguments for government support of science. The major argument is that basic science produces economically useful knowledge that has the characteristics of a public good — once produced it benefits others at low costs (non-excludability) and the value of its use is not depleted by the fact that others use it (non-rivalry).

Common for these contributions is the implicit assumption of a linear, one-directional causality from science to technology and from technology to economic development — the so-called *linear model*. The conceptual model depicted in Fig. 1 synthesises this conventional belief, still pervasive today, assigning fundamental research the prime impulse behind most sophisticated working technology leading to economically significant impacts.

Such generally held conceptualisation of the innovation process became the most powerful rationale for assembling resources and devoting them to research in the second half of the twentieth century. This model, containing a not-so-implicit domination of R ("white-coated" science) over D ("scruffy" engineering), soon became a template for industrial corporations to organise their innovative activities [9].

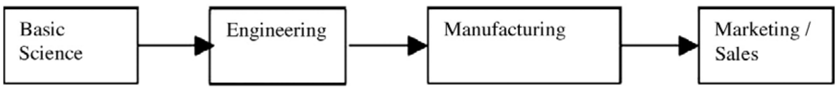


Fig. 1. The linear model. Source: Rothwell (1994, p. 41), [5].

[2] We are well aware of the 'five generations' model developed by Roy Rothwell [5]. We have simplified the analysis neglecting what he refers to as the second generation demand driven phase while the model that we propose may be seen as integrating elements from his fourth and fifth generation models but with more emphasis on the organisational dimension of the innovation process. We believe that simplification may be a powerful tool when it comes to capture new trends. While the chain-linked model introduced the importance of markets and feedbacks from external users our model adds the organisational dimension and its crucial impact on processes of interactive learning. In general we would argue that the different models presented as different generations co-exist in time both in the real world and in the minds of scholars and policymakers. What we propose is not to be thought as representing a new stage but rather a more complete analytical grid that makes it possible to capture the most salient features of the innovation process.

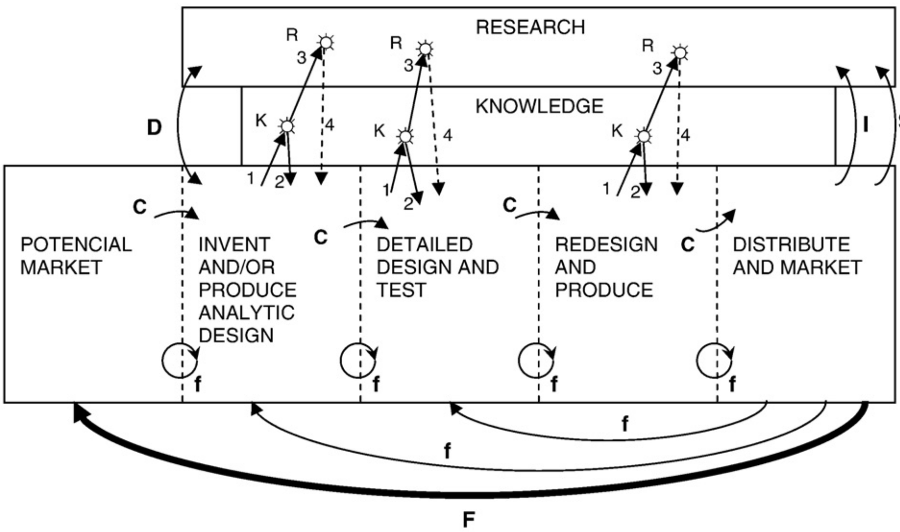
[3] In a recent paper Godin [6] argues that the reason why the linear model remains strong in the minds of analysts and policymakers is that the kind of statistics and indicators that they have access to seem to be more reliable when it comes to measure R&D than statistics and indicators referring to other factors. This points to the importance of developing indicators referring to linkages and organisational practices.

However, as state-led economic intervention lost political favour, governments increasingly became hard-pressed to justify the allocation of scarce financial resources to a science system that seemed to largely govern and evaluate itself. And the innovation outcomes that did not reflect the investments in science that appeared at the national and the international levels were designated as “paradoxes”. In time, the model opened the door to the more recent pressure for science to demonstrate its economic value and even to engage directly in commercial activities such as patenting. The positive assertion about causality from science to industry has in effect been reversed to a normative imperative of social legitimisation from market to academia. The queen is being asked to serve as a maid.

3. The chain-linked model

The linear perspective has been challenged not least by modern innovation theorising and empirical research. In the words of Kline and Rosenberg [10] “innovation is neither smooth nor linear, nor often well behaved.” Their *chain-linked model* is an influential and widely-cited focusing device for making sense of the complex structure and diversity of patterns of the innovation process. Kline and Rosenberg provide us with an important and influential theoretical standard for understanding the nature of continuous innovation, that is, the new application of either old or new knowledge to satisfy individual and collective demands. According to them a realistic conceptualisation of the innovation process must take it to be a series of changes resulting from the interplay of two forces, leading way to a highly uncertain process: an ongoing and ultimately uncertain transformation process intertwining commercial and technological opportunities and constraints. Thus, “in a complete picture we must recognize not only that innovation draws on science, but also that the demands of innovation often force the creation of science” [11].

The chain-linked model, in Fig. 2, shows flow paths of technical development that do not start with research, but with a broad idea of potential market use that is translated into a design or prototype initiating a cycle of feedback loops (f) eventually connecting back to users needs. Along any stage of this central process (C) accumulated scientific knowledge needed for innovation can be drawn upon (K) or new knowledge can be created in response (R). Sometimes new science can give rise to radical applications (D), while at other times science can benefit from innovations (I,S).



Chain-linked model showing flow paths of information and cooperation.
Symbols on arrows: **C** = central-chain-of-innovation; **f** = feedback loops; **F** = particularly important feedback.

K-R: Links through knowledge to research and return paths. If problems solved at node K, link 3 to R not activated. Return from research (link 4) is problematic - therefore dashed line.

D: Direct link to and from research from problems in invention and design.

I: Support of scientific research by instruments, machines, tools, and procedures of technology.

S: Support of research in sciences underlying product area to gain information directly and by monitoring outside work. The information obtained may apply anywhere along the chain.

Fig. 2. The chain-linked model. Source: Kline and Rosenberg (1986), [10].

One key insight of Kline and Rosenberg is that the stored validated knowledge we call science is not only drawn upon, but also produced in the process of innovation: it is part of the process, but not necessarily the initiating step. In other words, the D of R&D is, if anything, as important as R.

4. A third innovation model: the multi-channel interactive learning model

This paper refers back to Kline and Rosenberg's influential work and suggests key ideas for re-assessing the chain-linked conceptualisation through a new framework that we refer to as a *multi-channel interactive learning model*. The objective is thus to provide a third model that updates, complements and extends Kline and Rosenberg's perspective of inter-connected innovation steps. This new proposal enlarges their main insights and re-locates the innovation process in the context of 'the learning economy' [12].

Like Kline and Rosenberg's model, our model is centred at the enterprise level, still the major generator of economic innovation in contemporary society. It preserves the basic sequential stages of the internal innovation process and the feedback between those stages, therefore emphasising one of the critical insights into successful innovation projects: the process of interaction between units and teams within the firm. In our model the chain is coiled over itself to fully encompass the dynamics of learning processes. Therefore, we do not discriminate where the first step in the innovation process is to be expected: it could in principle start anywhere. The outcome of learning can be either product or process innovations, or the creation of new market segments and new approaches to organise business routines.

The speed of change in technological opportunities and markets gives a competitive advantage to firms that are open and agile both in innovation and adaptation processes. How the firm organises itself and its interfaces with science and users becomes critical for its success [13]. While the chain-linked view surpassed the linear model by emphasising the dynamic coupling between technological forces and market dynamics it did not explicitly acknowledge the organisational dimension and the wider institutional setting (the broader frame of institutions and socio-political subsystems of society, which influence innovation and are in turn influenced by it in a process of mutual adjustment) in which distinct forms of learning take place (not only about life and physical phenomena, but also about organisational and marketing problems).

Thus, the innovation process does not happen in a vacuum, but rather as a response to influencing, enabling and constraining factors. There is a near environment with actors and other organisations affecting the firm's innovation process – the *micro environment*, and in turn this is enveloped by a wider and evolving set of institutional structures, macro-economic, political, social, and ecological forces – the *macro environment*. The latter summarizes most of what is now known as external sources of learning and transactional relationships, sometimes appearing in the literature as sectoral [14] and regional systems of innovation [15]. At a more aggregate level we have the autonomous and semi-autonomous processes of social and institutional change and inertia known in the literature as national and continental systems of innovation [16]. The co-evolving micro and macro environments compose an innovation ecology, i.e. a complex multi-layered selection environment exerting shifting pressures on innovation processes at the enterprise level.

As the firm churns out new hypotheses and develops tentative new solutions to existing and evolving problems it will necessarily draw on information available in specialised fields of knowledge. But existing knowledge is continuously being revised and added to in response to the demands of innovation forcing the creation of new insights. In reality, there is no universal pool of knowledge from where we can learn, but rather a set of distinct *Knowledge Pools* that are relevant and complementary to the innovation process. In the context of the learning economy we consider three knowledge pools: i) knowledge about physical and biological science and technology, ii) knowledge about organisations and governance structures, and iii) knowledge about marketing techniques and customer behaviour.

An important feature of our model is the addition of *Interfaces*, or constructed channels of interpretation, which enable the firm to identify, select and absorb new ideas with productive potential from the firm's environment [17], namely from other actors and the knowledge pools. The interfaces are essential for learning as they open up the channels for interaction and cross-fertilization (Fig. 3).

If the internal innovation process spins at a relatively high speed then the micro and/or macro institutional set up may be thought of as lagging behind and causing a dampening effect on the innovation dynamics (although, obviously, the economy-wide system gains momentum if its actors are comparatively dynamic). On the other hand, if the character of the innovations being proposed at the organisational level and the older institutional framework are at odds with each other ('mismatch') then one can anticipate periods of turbulent transition and adjustment towards new techno-economic paradigms [18]. Finally, the learning process may materialise in product or process innovations or in the discovery of new market segments and new approaches to organising business routines. This concept of innovation provides the framework of the 3rd edition of the OECD Oslo Manual [19].

Our model has *representational* purposes and not representative ones, i.e. it does not assume that all factors have to be in place for innovation to be realised and successful. Rather, it tries to provide a stylised representation of the main classes of variables, and their interrelationships, which are involved in the innovation process taking place in a wide array of industries. For instance, innovative firms in 'low-tech' industries such as food-processing or textiles work closely with users in order to modify their products [20], whereas services firms in the finance sector are relatively heavy users of economic findings (econometrics, risk theory, etc.) [21], and, moreover, all of these are examples of industries quite dependent on equipment suppliers (machinery, information technology, and others) [22].

Thus, the model is an analytical grid that describes and contextualises elements, but it also provides a set of flexible generalisations upon which to base our thinking when trying to explain the sources and stages of the innovation process. It points

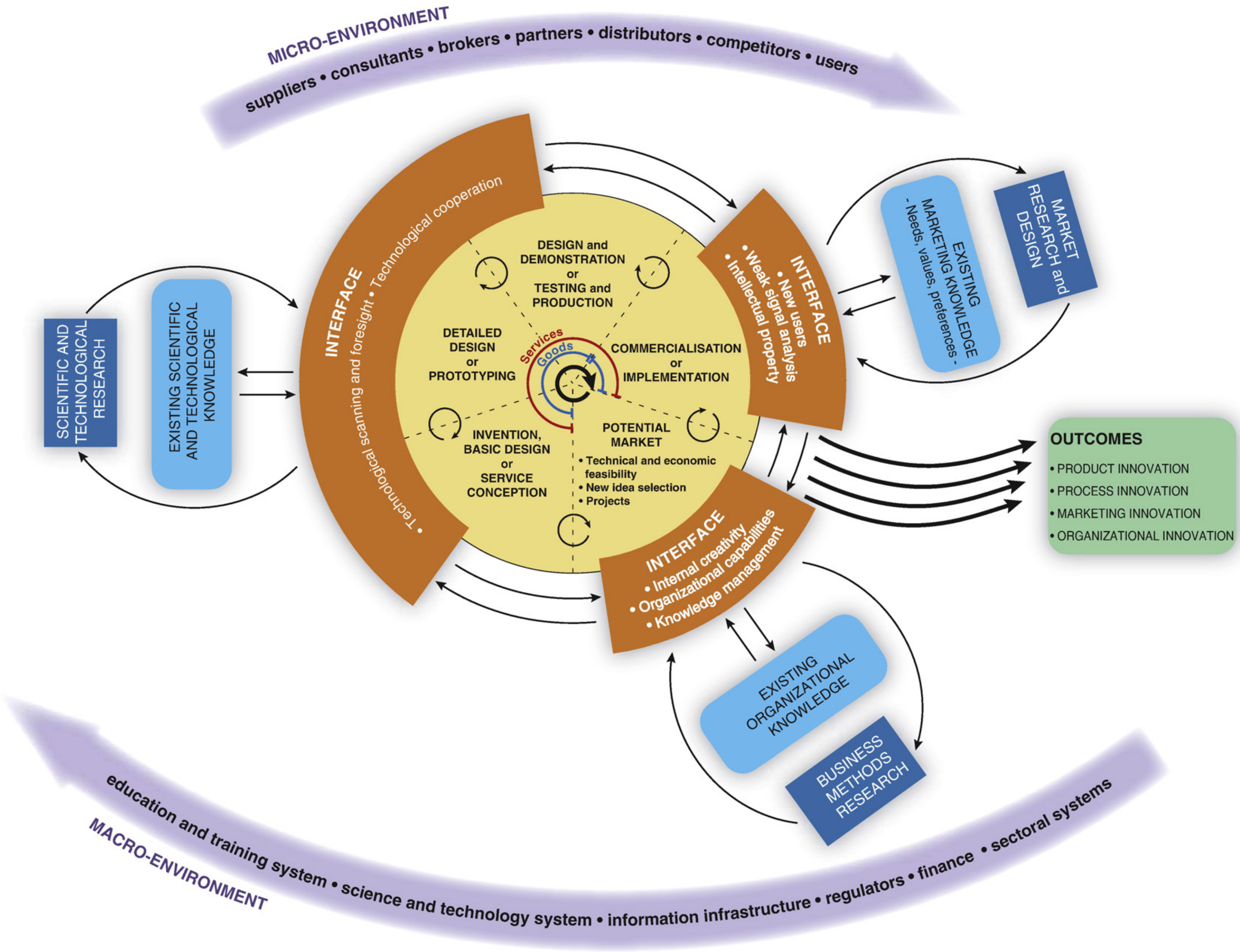


Fig. 3. The multi-channel interactive learning model. Source: J. Caraça et al. (2006), [1] and text.

to the ubiquitous experience-based learning processes taking place within firms, as well as at the interfaces with users, suppliers and competitors. In addition, in the interaction with universities and other science institutions, the daily exchange of knowledge involving scholars and students in an interaction with firms is more important than when universities act as business enterprises selling knowledge in the form of patents [23].

The model makes it clear that not all processes of innovation are science-based and that few of them are purely science-driven [3]. Moreover, as Kline and Rosenberg themselves had noted, and we want to emphasise, science tends to be "employed at all points of the central-chain-of-innovation, as needed" [10]. It has been pointed out that R and D are becoming seamless; corporate scientists are becoming more intimately familiar with implementation problems, being moved towards the front-office as "storm-troopers of innovation" [9]. Science is becoming ubiquitous in the innovation process in transition from R&D as two distinct and separate activities towards an increasingly strong and continuous engagement of science with production: R *as* D.

An implication is the following: if universities are to interact with such an evolving innovation process then they have to develop a broader knowledge bandwidth. This means gathering better organisational insights and marketing creativity without divesting from excellence in teaching and fundamental scientific research. As Theodor W. Hänch, 2005 winner of the Nobel Prize for Physics, reminds us: "For all the commercial temptations, however, basic research – the discovery of new knowledge – must remain top priority for any research university" [24]. Few activities have, indeed, been of more practical consequence than not-for-profit, curiosity-driven research.

5. Conclusions

Science remains a fundamental source of innovation, but in a plural knowledge context characterised by a multiplicity of intertwining channels where cooperation and technical information flows abound and take the form of learning processes. In order to transform the knowledge produced by R&D into commercial results, firms need to engage in interactive learning externally with customers and markets, and manage the feedbacks from the broader social and institutional environment. Today in the networked globalising learning economy the internal interaction across specialised functions continues to be equally important. Therefore, we have introduced a multi-channel learning model where research aiming at understanding markets and organisations appears on an equal footing with scientific research aiming at developing new technology and where experience-based learning is recognised as a prerequisite for transforming scientific knowledge into economic performance.

Interaction between science and industry is an important aspect of the innovation ecology; it contributes to the diversity of knowledge that is a defining feature of the sustainability of such systems. We have indicated that the science input needs to be seen as more diversified giving proper emphasis to human and social sciences relating to marketing and organisations. We have also argued that broader segments of industry will depend on science as strategic input for innovation. But it would be a mistake to use this as an argument to make universities and basic research subordinate to markets or to political dictates. It undermines the long-term viability of the innovation process and it neglects that the most important bottlenecks in the innovation process may have to do more with organisational forms that do not support experience-based learning in relation to markets and production. When policymakers assume that science is a direct source of innovation, or even the only major source, they tend to put too heavy a burden on the science part of the innovation system, including universities. When they do not see results corresponding to exaggerated expectations they assume that the problem is that universities are Ivory Towers, and respond with attempts to metamorphose universities into an equally inaccessible Towering Business.

The multi-channel interactive learning model presented here is complex and in this paper we have only been able to give a brief sketch. We hope it may serve as framework and inspiration for the formation of big-scale and ambitious research programs where the complete landscape of innovation is captured. It may also serve as a guide for policymakers who are exposed to different kinds of 'bias' — for instance focusing on the last vogue in international organisations or on what can be seen under the lamppost of innovation indicators.

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