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## **Linking research, finance and technological change. A conceptual framework**

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### **Abstract**

Understanding the pattern of technological change is a crucial precondition to formulate meaningful long-term research and industry policy. This paper therefore presents a conceptual framework explaining how the finance of early stage innovation activities influences the rate and direction of technological change.

Insights of neoclassical as well as heterodox economists, supported by countless real-life evidence, identify financial markets as far from perfect when it comes to innovation finance, and suggest state intervention to correct market and system failures. Here, the direct funding of R&D in selected technologies of interest represents an integral component of modern innovation policy. Given the proper institutional setup it offers a powerful tool to directly steer rate and direction of research activities. Indeed, throughout history many technological revolutions fundamentally changing our society, such as rail roads, modern ITC and biotechnology initially where triggered by massive government funded research programs before spilling into the private sector. Here, a major task for science and innovation policy is to facilitate the development of favorable R&D network structures leading to a rapid transformation of science into commercial technology. However, in general our understanding how governments interact with the system they try to affect is limited, and in particular the efficiency of public R&D funding is still under heavy discussion.

Yet, financial markets and their actors such as institutional investors, banks and venture capital firms represent the main intermediate link between savings and investments and are said to be pivotal to a smooth functioning of capitalistic economies, propelling economic growth in general, and facilitating innovation and entrepreneurship in particular. Through their decision to whom to provide capital and to whom not, public and private investors represent the major ex-ante selection device, every innovating firm and project has to face. Thus, with their allocation of resources, they play a major role in determining the rate as well as direction of technological change. Consequently, an investor perspective should be included as an integral component of industry and innovation policy. Here, a long tradition of research on behavioral finance advocates for the need of micro rather than macro level frameworks, since investment assessments are less an objective optimization process by fully rational agents, but rather a heuristic one by idiosyncratic agents acting under a bounded rationality. Since the set of information needed to fully assess an investments risk adjusted

returns in most cases is incomplete and the agents processing power is limited, their judgment will often be based on simple heuristics, rules-of-thumb and intuition. Further, this judgment is also subject to a set of cognitive biases caused by the agents beliefs, historical experiences, and social influences. Thus, investment decisions are made based on perception, which will differ between agents according to their existing knowledge, available information and cognitive biases. Here, theories of social influence and knowledge diffusion in networks offer great potential to render sources of information and potential cognitive biases altering investors capital allocation decisions.

As a consequence of the illustrated interdependence between public research funding, research networks, investors, and technological change, we are in need of a comprehensive framework helping to understand and shape our futures technology. I frame technological change as the reconfiguration of interaction pattern between technological artefacts induced by research activities of interconnected actors, and transferred from the theoretical to the commercial space by an as well interconnected population of investors with idiosyncratic rationales. I demonstrate how this process can be conceptionally understood, and empirically analyzed, as the evolution of a multi-layer network spanning through and across technology, research, and investor space.

I do so by first performing a systematic literature review of various scholarly disciplines engaged in discussions on technological change, finance and network dynamics, where I consider conceptual work as well as empirical findings. In a bibliometric analysis, I identify conceptual linkages, and in an empirical meta-analysis I align results of various streams of research. Grounded on the existing body of research, I develop a discipline-spanning theoretical model of finance induced and network mediated technological change. Finally, I present a simple mathematical formalization of this framework and compare first preliminary results with real-life data.

I thereby aim to contribute to multiple strands of literature by linking micro interactions within and between entities in investment, research and technology space to macro-outcomes such as investment trends, the establishment of scientific paradigms, technological trajectories, and technological change in general. These insights are valuable for the establishment of long-term industry and innovation policy, particularly in sectors subject to severe market and system failures while at the same time in need of extensive structural and technological change, such as for instance the energy sector. The paper also offers implication for investors, since it facilitates the prediction of technological trends by understanding the ongoing reconfiguration of technological systems as a function of investments and investor rationales, R&D activities and networks.

# Networks: The missing link between innovation finance and technological change. A conceptual framework\*

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# 1 Introduction

“I think the next century will be the century of complexity.” -Stephen Hawking

Understanding the pattern of technological change is a crucial precondition to formulate meaningful long-term research and industry policy. This paper presents a conceptual framework explaining how the finance of early stage innovation activities influences the rate and direction of technological change.

Insights of neoclassical as well as heterodox economists, supported by countless real-life evidence, identify financial markets as far from perfect when it comes to innovation finance, and suggest state intervention to correct market and system failures. Here, the direct funding of R&D in selected technologies of interest represents an integral component of modern innovation policy. Given the proper institutional setup it offers a powerful tool to directly steer rate and direction of research activities. Indeed, throughout history many technological revolutions fundamentally changing our society, such as rail roads, modern ITC and biotechnology initially where triggered by massive government funded research programs before spilling into the private sector. Here, a major task for science and innovation policy is to facilitate the development of favorable R&D network structures leading to a rapid transformation of science into commercial technology. However, in general our understanding how governments interact with the system they try to affect is limited, and in particular the efficiency of public R&D funding is still under heavy discussion.

Yet, financial markets and their actors such as institutional investors, banks and venture capital firms represent the main intermediate link between savings and investments and are said to be pivotal to a smooth functioning of capitalistic economies, propelling economic growth in general, and facilitating innovation and entrepreneurship in particular. Through their decision to whom to provide capital and to whom not, public and private investors represent the major ex-ante selection device, every innovating firm and project has to face. Thus, with their allocation of resources, they play a major role in determining the rate as well as direction of technological change. Consequently, an investor perspective should be included as an integral component of industry and innovation policy. Here, a long tradition of research on behavioral finance advocates for the need of micro rather than macro level frameworks, since investment assessments are less an objective optimization process by fully rational agents, but rather a heuristic one by idiosyncratic agents acting under “bounded rationality” ([Simon, 1955](#)). Since the set of information needed

to fully assess an investment's risk-adjusted returns in most cases is incomplete and the agents' processing power is limited, their judgment will often be based on simple heuristics, rules-of-thumb and intuition. Further, this judgment is also subject to a set of cognitive biases caused by the agents' beliefs, historical experiences, and social influences. Thus, investment decisions are made based on perception, which will differ between agents according to their existing knowledge, available information and cognitive biases. Here, theories of social influence and knowledge diffusion in networks offer great potential to render sources of information and potential cognitive biases altering investors' capital allocation decisions.

As a consequence, we frame technological change as the reconfiguration of interaction patterns between technological artifacts induced by research activities of interconnected actors, and transferred from the theoretical to the commercial space by an as well interconnected population of investors with idiosyncratic rationales. I demonstrate how this process can be conceptually understood, and empirically analyzed, as the evolution of a multi-layer network spanning through and across technology, research, and investor space.

I do so by first performing a systematic literature review of various scholarly disciplines engaged in discussions on technological change, finance and network dynamics, where I consider conceptual work as well as empirical findings. In a bibliometric analysis, I identify conceptual linkages, and in an empirical meta-analysis I align results of various streams of research. Grounded on the existing body of research, I develop a discipline-spanning theoretical model of finance-induced and network-mediated technological change. Finally, I present a simple mathematical formalization of this framework and compare first preliminary results with real-life data.

I thereby aim to contribute to multiple strands of literature by linking micro interactions within and between entities in investment, research and technology space to macro-outcomes such as investment trends, the establishment of scientific paradigms, technological trajectories, and technological change in general. These insights are valuable for the establishment of long-term industry and innovation policy, particularly in sectors subject to severe market and system failures while at the same time in need of extensive structural and technological change, such as for instance the energy sector. The paper also offers implications for investors, since it facilitates the prediction of technological trends by understanding the ongoing reconfiguration of technological systems as a function of investments and investor rationales, R&D activities and networks.

## 2 The framework

The advantages of heterogeneous groups of actors are well established in social science. [Simmel \(1955\)](#) to [Merton \(1957\)](#) to [Granovetter \(1973\)](#) to [Burt \(1992\)](#).....

### 2.1 Complexity theory, networks and technological progress

Social, technological, biological and information systems all share, if anything, the characteristic of inherent complexity ([Simon, 1991](#)). As the “language of complexity”, such systems are often described as networks that have a topology of interconnected elements combining organization and randomness [Boccaletti et al. \(2006\)](#); [Newman et al. \(2006\)](#).

[Strogatz \(2001\)](#): From the perspective of nonlinear dynamics, we would also like to understand how an enormous network of interacting dynamical systems — be they neurons, power stations or lasers — will behave collectively, given their individual dynamics and coupling architecture. Researchers are only now beginning to unravel the structure and dynamics of complex networks.

This stream of thought has also brought a fresh perspective social science.

Furthermore, a brief reality check makes us also question the boundaries of the system. All the really complicated things, such as the collective formation of value and meaning, cultural norms, attitudes, policy, regulation and so forth I - as so many others - collect under the umbrella term “institutions” and assume them to be exogenous. They represent a main part of the systems initial conditions as well as its mechanisms. They determine the selection criteria and thereby population dynamics of the systems entities as well as the criteria how this entities create links, and how these links influence them. In reality -society and institutions also shaped by technology -investments also -but institutions more stable over time, even though change accelerated by technology

## 3 The Research Layer

Nowadays it is well perceived that invention and innovation - the essence of technological change - is above all a social process not happening in isolation ([Powell et al., 1996](#)). A large body of literature from all strands of social science - economics, organizational and management studies, sociology, psychology, economics *et cetera* - offers various and nuanced insights on why

and how firms and individuals draw a fair share of their inputs for the development of novelties from their network.

During the early 1990<sup>s</sup>, scholars in management and organizational science started to focus on the importance of internal (*knowledge-based view*: eg. (Grant, 1996; Kogut and Zander, 1992; Spender and Grant, 1996)) and external (*network-based view*: eg. (Lavie, 2006)) knowledge stocks accessed via alliances Grant and Baden-Fuller (2004) to develop dynamic capabilities (Teece et al., 1997) and maintain a sustainable competitive advantage (Dierickx and Cool, 1989).

Around the same time, economists started to embrace systemic approaches to the economy in general, and innovation and technological change in particular (Freeman, 1987; Lundvall, 1992; Nelson, 1993). Here, economic development is envisioned as the outcome of the interaction between various subsystems and embedded heterogeneous economic agents (Hanusch and Pyka, 2007; Pyka, 2002).

Since, cascading research has created awareness how a firm's strategic positioning in inter-organizational networks affects its innovative performance (e.g. Baum et al., 2000; Fleming et al., 2007b; Powell et al., 1996; Stuart, 2000). Not only the firm-centered ego-network positions but also the overall typologies of large-scale innovation networks have been shown to affect the innovative performance of firms (Schilling and Phelps, 2007) as well as entire networks (Fleming et al., 2007a) and regions (Fleming and Frenken, 2007; Saxenian, 2001).

Research also shows that networks are by no mean static constructs in time and space, but rather constantly rearrange (Doreian and Stokman, 2005; Glückler, 2007; Powell et al., 2005), hence call for more dynamic and evolutionary approaches in empirical innovation network research (e.g. Ahuja et al., 2007; Cantner and Graf, 2011). Recent findings suggest that - as in every complex system - the development of such research networks is very sensitive to internal and external initial conditions such as heterogeneity of the industry structure (Hain et al., 2014) or actor strategies (Hain and Jurowetzki, 2014).

## 4 The Technology Layer

The seminal work of Kuhn (1962) illustrates how science develops in a path dependent manner within a *scientific paradigm*, which can be understood as framework of accepted concepts, results, and procedures within which subsequent work is structured. The progress of normal science normal science is usually bounded by the structure of problem solving processes within such

paradigms, hence usually focuses on incremental extensions of relationships, the refinement of agreed ones, and the increase of measurement precision.<sup>1</sup> However, discoveries fundamentally contradictory to what is universally accepted can at some points of time lead to epistemological paradigm shifts, which [Kuhn \(1962\)](#) labels as “scientific revolution”.

Since scientific and technological development have always been closely linked, we similarly understand *technological paradigm* as “*a set of procedures, a definition of the relevant problems and of the specific knowledge related to their solution*” ([Dosi, 1982](#)). While such *relevant* problems are formulated in a societal discourse, the selection of procedures to address them are determined by technological and economic trade-offs. Even though...

To apply complex system analysis to such problems, it becomes useful to dis-aggregate technology in elements and their interactions. For the following, let us define technology according to [Dosi \(1982\)](#) as “*a set of pieces of knowledge, both directly practical (related to concrete problems and devices) and theoretical (but practical, applicable although not necessarily already applied), know-how, methods, procedures, experience of successes and failures*”. To map and understand technological systems, [Jurawetzki and Hain \(2014\)](#) a decomposition of technological knowledge on different levels.. On the lowest level, we find what we call *technology fragments*, which are atomic, non-reducible repositories of scientific/technological knowledge needed to fulfill a certain and narrow task. In scientific, technological and industrial applications such as machines, software and other devices labeled *technological artifacts*, such fragments are linked in a functional relationship to produce some output. On a again higher level, sets of complementary and substitutional artifacts form a a *technological field*. Over time, such field develop along Dosian technological trajectories, where accumulated sets of common configuration pattern partially reproduce over time and set the foundation for further combinations. Hence, higher levels of aggregation are formed by the pattern of connection between atomic fragments of technological knowledge, where this connection can be understood very abstract as the fragments degree of interaction. Such a framework is surely a crude simplification of technological change, which always happens in a social context ([Bijker, 1997](#); [Bijker et al., 1987](#); [Hughes, 1987](#)).

However, for the sake of analytic orthogonality, it is convenient at this point to neglect the social dimension and just focus on how technology resembles purely in technology space. Drawing analogies from evolutionary biology ([Dawkins, 1976](#)), one might imagine “the selfish technology”,

<sup>1</sup>As at its time famously claimed by Lord Kelvin: “There is nothing new to be discovered in physics now. All that remains is more and more precise measurement.”

trying to gain an edge in its selection environment, independent of how the formation of this environment. We now can assume our technology fragments to act “as if” they were conscious agents striving to improve their reproduction probability by reconfiguration their interaction pattern with other fragments.<sup>2</sup>

in such settings, the concept of NK “fitness landscapes”<sup>3</sup> from evolutionary biology becomes useful to analyze selection processes as stochastic combinatory optimization in complex systems. In its core, such a landscape represents a multidimensional mapping of components with attributed states of solution parameters to some measure of performance representing an elements fitness (Kauffman, 1993). In this fitness dimension, the landscape shows high performance “peaks” as well as low performance “valleys”, where the peaks can be understood as the “evolutionary frontier”, the highest reachable level of a certain evolutionary path with respect to relevant environmental conditions. In the classical model proposed by Kauffman (1993), biological evolution of complex organisms, in which the functioning of genes is interdependent, has been analyzed as “hill-climbing” activity on NK fitness landscapes through random mutation and natural selection.

Since the components are epistatically related, their fitness depends not only on their own states but also the “interaction” with their neighbors. The systems complexity is determined by the number of its components and their degree of epistasis, and manifests in the “ruggedness” of the landscape (Levinthal, 1997). Simple systems with a small set of components and/or low epistatic relations among them correspond to smooth landscapes with a few evenly distributed peaks, whereas a complex ones corresponds to a landscape with many unevenly distributed peaks of varying height. A main insight derived from such models is the efficiency of different evolutionary processes. With increasing complexity and associated ruggedness of the landscape, it becomes more and more unlikely that pure local selection will lead to globally optimal outcomes but rather to a lock-in into locally optimal *evolutionary pockets*.

In technology space, this evolutionary metaphor has also proven to provide powerful implications for technological change in complex systems. First, with increasing complexity of the technological/scientific paradigm one is operating in, the more important become exploration ori-

<sup>2</sup>The economic *pendant* here would be the “as-if” hypothesis Friedman (1953) of positive economics.

<sup>3</sup>where  $N$  denotes the system's number of components ( $i = 1, \dots, N$ ), and  $K$  the number of epistatic relations every component shares with others.

ented research strategies in contrast to local incremental exploitation of already existing solutions (March, 1991).

## 5 The Investment Layer

The pivotal role of finance in facilitating innovation and propelling technological change is already emphasized the work of Schumpeter (1942), who claims innovations based on credit creation as the force behind capitalist dynamics. However, it has also been recognized that investments in innovation appear to be substantially different from other forms of investments (Hall, 2010; Hall and Lerner, 2009). Early work (Arrow, 1962; Nelson, 1959) commonly associates innovation and technological progress with investments in R&D, and argue that knowledge spillovers lead to incomplete appropriation of their results, hence decrease firm/investors incentives to carry out such investments. Subsequent research during the last decades has provided manifold examples as well as a more nuanced understanding how the design of financial systems (Dosi, 1990), the behavior of investors on financial markets Perez (2002, 2004, 2009), public funding (Mazzucato, 2011) and firm level resource allocation (Tylecote, 2007) massively impact the rate and direction of technological change. Yet, the vast majority of research on technological change focuses on the behavior of researchers/inventors and innovators/entrepreneurs (the link between  $D1$  and  $D2$ ), while neglecting financial agents.

However, allocation decisions on external financial markets as well as in internal corporate finance nowadays represent the major *ex-ante* selection device every innovating firm and project has to face, thus are central in determining the amount of innovative effort, and its trajectory .

In general, investors primarily aim to adjust the risk-adjusted returns of their investments. The risks investors commonly consider are related to the (i.) firm/project invested in, (ii.)the technology deployed, (iii.) the market it sells in, and (iv.) policies that might influence it. Where the first is specific to the investment, the latter are systemic. As a simple rule, investors will require higher returns for riskier investments in order to maintain a certain level of average returns.

$$\max_{0 \leq k \leq N} \Pi_i^k(\delta_i^k, c_i^k) \quad (1)$$

Yet, it seldom is that simple. First, not only the average, but also the variance of returns matter. Assuming investors per se to be risk averse, given the same risk ad-justed returns, they will tend to choose the investment with less variance. Second, different investors will have different risk preferences, and specialize on certain risk-return-variance levels. While institutional investors such as pension funds usually show a very low risk tolerance and require only modest returns, venture capitalists invest in highly risky targets but therefore require extraordinary returns. Third, a long tradition of research on behavioral finance tells us that this risk/return assessment is less of an objective optimization process by fully rational agents, but rather a heuristic one by agents acting under “bounded rationality” (Simon, 1955). Since the set of information needed to fully assess an investments risk adjust-ed returns in most cases is incomplete and the agents processing power is limited, their judgment will often be based on simple heuristics, rules-of-thumb and intuition (Tversky and Kahneman, 1974). Further, this judgment is also subject to a set of cognitive biases (McFadden, (2001) caused by the agents believes, historical experiences, and social influences. Thus, investment decisions are made based on “perceived risk”, which will differ between agents according to their existing knowledge, available information and cognitive biases. Besides optimizing perceived risk-adjusted returns of their portfolio, some investors in RE also integrate social, environmental, and ethical considerations into their decision making (Renneboog et al., 2008). Moreover, financial constraints are in the financial literature said to stem from problems de-rived from asymmetric information between borrowers and lenders (Akerlof, 1970). Because energy systems are highly integrated and interdependent, these problems are likely to be multiplied.

To sum up, investors care about risk-adjusted returns and their variance, have different risk tolerance, and assess individually ‘perceived risk’ under bounded rationality. Even though still subject to imperfect information and cognitive biases, this assessment will become more precise when investors undertake the effort of gathering a more complete set of information on investment and context, and applied heuristics improve with increasing investment experience and knowledge relevant for the particular invest-ment. Therefore, capital markets are characterized by a division of labor and specialization, which is expe-dient when investors need to cope with complex and asymmetric information in the market. Investors might specialize on investments in firms of certain characteristics (start-ups, mature firms), deployed technologies (ICT, biotech, RE), asset classes (VC, PE, loans, project finance), risk profiles (low, high) et cetera. Specializing on one or

more of this investment characteristics results in a particular set of relevant investment targets and information needed for their assessment. This accentuates that to obtain a prop-er analysis and understanding of investments in RE or elsewhere, a nuanced and disaggregated reflection of the structural composition of investors and investments is vital.

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