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Innovation and Lock-in

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Abstract

This study focuses on a well-known but yet elusive concept: (technological) *lock-in*. We summarize what is known about the nature of *lock-in* and offer a critical view on history-dependent processes based on recent contributions to the literature. We discuss if *lock-ins* are really inescapable, especially when innovation is concerned. Also, we address the question if *lock-in* is a well-defined concept at all. To offer a fresh view on *lock-in* and to tackle the issues just raised, we employ the replicator dynamics model. By making a parallel between monopolization in the replicator dynamics and the occurrence of *lock-ins*, we show that the convergence of a system to a given outcome can be reversed, under certain conditions. We highlight the need for a more precise demarcation of the conceptual boundaries of *lock-in* and path dependence, both from the formal and the empirical side, and suggest that further structural features – for example users heterogeneity – may play a relevant role in affecting the outcome of dynamic allocation and competition processes.

Keywords: Lock-in; path dependence, history dependent processes; innovation; competitive diffusion; Polya urn.

JEL Classification: L15; O31; O33.

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1. Introduction

The concept of *lock-in* can certainly be listed among those weighing most in the conceptual toolbox used by scholars of innovation and evolutionary economics. Processes of competitive diffusion, or choice between alternatives of 'unknown merit' (Arthur, 1989), are known to generate *lock-in*, that is inflexible outcomes, and this finding has critical implication for the study of economic dynamics. In fact, the very existence of *lock-in* outcomes relies on the acceptance of non-equilibrium, non-optimal, and history-dependent processes. However, it is somehow ironic that an evolutionary-inspired notion describes a situation that resembles that of rest, a structural equilibrium of a dynamic system. This seemingly paradoxical situation emerges from the fact that *lock-ins* are outcomes, rather than determinants, of processes (of adoption, or of choice). Therefore, to focus one's analysis only on *lock-ins* limits the understanding of the processes unfolding over time that may lead to them. Focusing on the whole process and set of conditions that generate locked-in situations may shed further light on the inflexible nature of certain technological and market outcomes, and on the inescapable attraction of some states of the worlds compared to other, competing ones.

In this Chapter, we summarize what is known in the economic literature about the nature of *lock-in*, and we discuss if *lock-ins* are really inescapable, especially when innovation is concerned. Also, we address the question if *lock-in* is a well-defined concept at all. To offer a fresh view on *lock-in* and to tackle the issues just raised, we employ the replicator dynamics model (Metcalfe, 1994). The replicator model is traditionally used in economics to represent the Schumpeterian 'competition for the market' (Cantner, 2011) and market share dynamics, but can also consistently capture the evolution of the frequencies of given competing alternatives (technologies, products, etc.) over a whole alternatives space to assess if the dynamical system converges towards states of monopolization or dominance of one

alternative. We make a parallel between monopolization and *lock-in*, and we show that the convergence of a system to such dominance of a single alternative does not have to be inescapable, and it is strongly dependent on the regime and parameters characterizing the competition. To support this view, we offer a critical view on history-dependent processes based on the insights of recent contributions to the literature. These contributions highlight the need for a more precise demarcation of the conceptual boundaries of *lock-in* and path dependence, both from the formal and the empirical side, and suggest that further structural features – for example users heterogeneity – may play a relevant role in affecting the outcome of dynamic allocation and competition processes.

The concept of *lock-in* is deeply interconnected with that of path dependence, given that one is the cause of the other; the direction of causality varies according to the particular characterization followed for the *lock-in*. Therefore, in what follows, we will refer to both of them together most of the times. The two terms are not to be considered synonyms (because they are not), but a separate treatment of path dependence and *lock-in* risks to leave aside some of the multifaceted dimensions of the phenomenon of interest.

The Chapter proceeds as follows: in Section Two, we define *lock-in*, we relate it to path dependence and we overview the fields in which the notion has been used more successfully. In Section Three, we discuss if *lock-in* is an inescapable state of affairs or just a transitory situation. Factors that make *lock-in* unlikely are discussed, with a prominent role reserved to the introduction of novelties into the competition between alternatives. In Section Four, we use the replicator dynamics to model the interaction between selection-driven increasing returns and alternative-specific improvements with decreasing returns in order to allow a system to diverge from monopolization outcomes; we interpret this as an additional evidence that *lock-ins* are not inescapable. Section Five concludes.

2. Lock-in in the literature

Lock-in: feedbacks and incontestability

The concept of *lock-in* owns its fortune in economic theorizing to David (1985) and Arthur (1989), who succeeded where many economists failed before: breaking with the abstract and a-historical view of economic processes, and to remind (and, in some cases, convince) fellow economists that 'history matters'. In a nutshell, *lock-ins* can be considered as 'inflexibilities' of outcomes. As Arthur (1989) points out, inflexibility is one of the properties of dynamic allocation problems – such as that of choices between competing technological alternatives – featuring (dynamic) increasing returns (or positive feedbacks). Increasing returns at play – that is, a situation in which an increase of an action, for example consumption, investment, or technology adoption, by x % yields to returns (e. g. utility, profits, gains from technology use, efficiency) of more than x %, or in other words to more than proportional positive feedbacks – are known to generate multiple equilibria, non-predictability and potential inefficiency of outcomes. Small, accidental events, driven by chance, can be 'magnified' by positive feedbacks so much to make history – that is, the path of allocations or choices – relevant and to drive the dynamical system to one or another of its possible equilibria. Putting all together, "once an outcome (a dominant technology) begins to emerge it becomes progressively more 'locked in'" (Arthur, 1989, p. 117), meaning that the more history unfolds, the possible worlds and trajectories do not maintain the same ex ante probability of happening; by this the system becomes less and less flexible, and one of the outcomes eventually is selected even if it may not be the 'superior' one. Although the very definition of superiority of one alternative with respect to the others can be a subject of debate – especially with respect to the criteria used to identify superiority –, the bottom line of the story is clear: a recipe combining random

accidents, increasing returns and choice over alternatives that unfolds in time creates the conditions for *lock-in* to occur.

A caveat is here in order before proceeding further with the analysis. The 'recipe' just mentioned is dissected and discussed in the following at a rather abstract level of analysis, to gain advantage of the formal representation of *lock-in* and path dependence. It goes without saying, that *lock-ins* at the level of technologies, actors, and whole systems are always the emergent outcome of networks of interaction that endogenously set the conditions for outcomes' inflexibility and prevalence. In turn, such networked interactions are deeply rooted in unique (environmental, social, cultural) contexts that certainly play a role in affecting the rate, direction and result of the processes object of analysis. Such embeddedness cannot be trivially introduced in the model proposed in this Chapter. Hence, in what follows, it is left on the background. However, that does not mean that a contextual embeddedness of path-dependent processes does not exist at all; the environmental, social and cultural roots of technological and system emergent outcomes have to be included in the analysis any time scholars pass from formal analysis to policy implications.

Increasing returns may arise either on the supply side of a market as a result of learning effects (all the 'learning-by' concepts such as learning-by-doing or learning-by-using) or on the demand side as a result of positive network or agglomeration externalities/effects (Klemperer, 2008) that raise the benefits of a technique, product, or location for each user as the total number of users increases. As one alternative, due to chance, gets a head start in diffusion, for example by passing a certain threshold of users, increasing returns narrow the degree of freedom for the system to switch to another or to significantly change the direction of the current trajectory, disregarding the 'goodness' of the trajectory taken.

Another way to see inflexibility is as *incontestability*: here one of the alternatives is so *prevalent* that others cannot contest it. According to David (1985; 1987) *prevalence* is affected not just by dynamic increasing returns (due to the mentioned learning or network effects), but also by the technical interrelatedness of system components, and quasi-irreversibility of investment – both of which can be expressed more generally, in terms of switching costs. The technical interrelatedness of a system appears to be an aspect very much out of the economic realm: chemical and physical laws, as well as engineering types of relationships, presumably determine which kinds of technologies fit together, which ones may be substituted, and which complementarities cannot easily be challenged. Such systems often require high investments, which in turn are characterized by quasi-irreversibility, and quasi-irreversibility implies that changes are related to – often very high – switching costs. This translates the previous argument of systemic interrelations into economic cost terms. For example, the switching costs related to the resources required to explore new chemical and physical laws or engineering relationships, which allow for breaking up the existing interrelations, are very (if not infinitely) high. In other cases, it is the systemic dimension of the supply of the goods and services related to a certain technology which protects against the challenges of new invader technologies – the combustion engine for automobiles and the accompanying system of fuel stations and fuel logistics just being a point in case. Combined with these investments are mutual dependencies – not only of a technical nature but also in terms of relative prices – which contribute to the prevalence of the core technology. As long as relative factor price changes remain in a certain range, switching costs to new alternatives prevail high and, hence, secure the persistence of the existing technology.

Farrell and Klemperer (2007) explore in details the role network externalities and switching costs play in an industrial organization framework that is concerned with firms' entry and exit dynamics, pricing, contracting, competition, efficient scale, and so on. While for the authors

none of the two elements are problematic by definition for market dynamics, their very existence requires at least policy attention to avoid coordination failures. In fact, the main issue that the notion of *lock-in* suggests has to do with losses of efficiency: users may be better off under the alternative state of the world, but the history dependent process makes the 'best' scenario unfeasible.

Lock-in: the chicken-and-egg problem

Conceptually, while from the Arthur and David papers introduced above *lock-in* appears as an ex post outcome produced by a specific property of dynamic allocation problems with increasing returns, that is, inflexibility, other scholars consider *lock-in* as a *cause* for path dependence. For example, Page (2006), defining path dependence, suggests that:

A survey of the literature on path dependence reveals four related causes: increasing returns, self-reinforcement, positive feedbacks, and lock-in. Though related, these causes differ. Increasing returns means that the more a choice is made or an action is taken, the greater its benefits. Self-reinforcement means that making a choice or taking an action puts in place a set of forces or complementary institutions that encourage that choice to be sustained. With positive feedbacks, an action or choice creates positive externalities when that same choice is made by other people. Positive feedbacks create something like increasing returns, but mathematically, they differ. Increasing returns can be thought of as benefits that rise smoothly as more people make a particular choice and positive feedbacks as little bonuses given to people who already made that choice or who will make that choice in the future. Finally, lock-in means that one choice or action becomes better than any other one because a sufficient number of people have already made that choice. (Page, 2006, p.88)

Besides the useful clarification provided by Page on how increasing returns, self-reinforcement, positive feedbacks and *lock-in* can be distinguished, and despite here *lock-in* is considered one of the causes, rather than an outcome of path dependence, the common feature of *lock-ins* is that they are forms of inflexibility. This general property has been considered key by scholars to understand the establishment of certain alternatives over others in disparate fields of technological competition: the QWERTY keyboard (David, 1985), VHS, nuclear power reactors (Cowan, 1990), electric vehicles (Cowan and Hultén, 1996), fossil fuels (carbon)-based energy systems (Unruh, 2000), eco-innovation (Cecere et al., 2014), just to name a few and to offer a non-exhaustive list. The inflexible and especially inefficient (read inferior) nature of some of the mentioned cases has been questioned recently (e.g. Kay, 2013) and we discuss that in the next Section. However, in general, the concept of *lock-in* offers a neat guiding principle to understand that technological competition without policy 'supervision' can generate undesired outcomes. At the same time, it suggests the possibility that policy intervention itself may generate those small historical events capable of driving the economic system out of a given path and to set it on another – inefficient – one without any further right of appeal – as a case of 'government failure'.

Lock-ins: beyond technological competition

The idea of inflexibility suggested by the concept of *lock-in* has seen a spectrum of applications and developments ranging far beyond the domain of technological competition. At the micro level, behavioral *lock-ins* are in general variations on the theme of informational cascades and herd behaviors (Bikhchandani et al., 1992), where choices tend to weigh external signals, conveying information of others, more than internal ones (such as intrinsic motivation) until one of the possible viable alternatives become inescapable. Informational effects work in this case in the same direction as network effects, with the only difference that

in the first case the information about a benefit is conveyed, while in the second case the benefit is directly obtained through adoption (Easley and Kleinberg, 2010).

At the macro level, more than *lock-in* it is path dependence that gained widespread usage in the literature. More precisely, the concept of path dependence has a parallel in the related – but not exactly equal – notion of *hysteresis* (Setterfield, 2009; Göcke, 2002). Hysteresis is defined as the 'permanent effects of a temporary stimulus' (Göcke, 2002); the concept, inspired by studies on magnetism, is mostly applied in the study of macrodynamics (e.g. 'strong' hysteresis in the labor market, or the persistence of natural rates like the NAIRU) and to inform econometric analysis of the historical component of the data generating process underlying some given variable. According to Setterfield (2009), hysteresis can be considered a special case of path dependence, where the latter serves more as an 'organizing concept' and its explanatory power does not relate only to persistence, but rather to the specific path of choices, decision or adoptions taken through history.

Addressing the meso level, path dependence and *lock-in* often overlap in usage with the notions of a standard, dominant design, and platforms (see e.g. Gallagher, 2007); while all these concepts are defined in different ways and refer to different objects, phenomena, or fields of analysis, they all share the nature of 'stable configurations' implied by the inflexibility property of *lock-ins*. Therefore, they can be considered representing constellations of *lock-in*.

Path dependence and *lock-in* found application in industry studies, in regional studies, and in development studies as well. Starting from the latter, development and structuralist economics recognizes path dependence and *lock-in* as fundamental categories to understand the success or failure of catching-up process. This holds on the one hand, at the country level, where

countries can rest on a path-dependent trail of underdevelopment leading to one of the many 'traps' waiting to slowdown the process of growth and structural change. On the other hand, path dependence matters at the firm level, where 'bygones are rarely bygones' and companies combine bounded rationality, routines, institutional frameworks, cooperation and competition, and bundles of resources and capabilities to build-up their unique evolutionary path and their dynamic capabilities (Cimoli and Porcile, 2015). The progressive sedimentation of firm-specific characteristics increases market heterogeneity which, combined with selective processes, give rise to restless industrial dynamics (Cantner, 2009). In regional studies, and even more critically in evolutionary economic geography (Martin and Sunley, 2006), path dependence and *lock-in* have been used to explain the success or failure of specific regions and clusters as well as patterns of regional diversification and resilience (Boschma, 2015). Juxtaposing *lock-in* and path dependence with the complementary concepts of path creation, path renewal, path dissolution, and *place dependence* (that is, dependence stemming from location rather than history), and complementing this perspective with notions and insights derived from the related fields of system transition and strategic niche management, evolutionary economic geography has set up the most ready to use conceptualization of *lock-in* at hand for policy makers (Boschma et al., 2016). Finally, industry studies such that of Bergek and Onufrey (2013) inductively derive from the observation of patenting activity in the lighting industry the richer and kaleidoscopic nature of path-dependent processes. To explain the existence of the multi-technology company and the co-existence of different technological alternatives, in fact, one has to delve more deeply into the very concept of *path*: while firms (or technological systems, at a higher level of aggregation) show the typical inflexibility of locked-in situations (persistence and the presence of positive feedbacks), such inflexibility may be grounded at a finer-grained level of detail in the co-evolution of parallel trajectories. The latter contribution suggests that the emergence of *lock-in* situation is far from being fully understood. The complexity of real world phenomena that display competition for

dominance between alternatives and inflexibilities remind us that the concept of *lock-in* has a valuable use for illustrative purposes, while – as we discuss later in the Chapter – it yet lacks the conceptual elaboration to make it a well-defined formal tool.

Finally, as we already mentioned briefly, the concepts of path dependence and *lock-in* have served to back competition policy and the claim that in presence of network effects tendencies of welfare-reducing monopolizations have to be contrasted with regulation (Liebowitz and Margolis, 1995). *Lock-ins* are therefore a form of dynamic market failure. However, recently the role played by (indirect) network effects has been found to be more complex, especially in so-called two-sided and multi-sided markets (Armstrong, 2006), where the interaction between different users with interdependent utilities mediated by network effects and by the existence of competing platforms providing an interface between the market sides may generate benefits thanks to *lock-ins*.

3. Lock-in – is it really inescapable? Is it really an issue?

Lock-in is usually conceived as a deadlock of technological competition or economic dynamics, where one of the competing alternatives – not always the superior one – becomes uncontestable. While such deadlocks do not have to be always welfare reducing (the very idea of standards is that they are sort of welfare enhancing *lock-ins* that reduce coordination and compatibility costs), the shrinking of the set of choices – especially if the alternative over which the system is locked into is inferior – may not be a desirable property of history dependent processes. The related questions at stake we deal with in this Section are two: first, if *lock-ins* are inescapable inflexible outcomes, and if the inflexibility they generate is only a temporary tendency; second, in any case, if *lock-in* is a well-defined concept at all.

Overcoming *Lock-ins*: the role of new alternatives

The debate on the real 'pressure' exerted by path dependence and *lock-ins* on technological and economic dynamics is still going on. For example, a 'revisionist' approach to the emergence of the QWERTY keyboard (Kay, 2013) suggests that QWERTY was already superior since the very beginning of typewriting, if the process is seen from a problem-solving perspective. Kay claims that re-running the tape of history we would have seen QWERTY to win over and over again against competing alternatives such as the DSK keyboard. Hence, path dependence and *lock-in* are criticized from their very foundational example; initial conditions, small events and accidents along the technology evolution path may play a less relevant role than previously thought. Along the same line, already Witt (1997) pointed out that the results of David's analysis and the Arthur model were strongly dependent on the design and the nature of the modeling strategy used, namely a generalization of the Polya urn scheme. In fact, such models assume as a starting configuration a 'virgin market condition', which is rarely the framework under which technological competition takes place; furthermore, the inescapable feature of *lock-ins* has no real counterpart in reality, were novel technologies continuously threaten, contest and displace existing alternatives. In a nutshell, innovation may be the reason behind the possibility to escape *lock-in*. Witt suggests to use an alternative modeling strategy (the master equation) featuring an incumbent-entrant race, and the existence of critical masses as threshold values that, when overcome, allow the new alternatives to revert *lock-ins*. The role played by 'diffusion agents' in arranging coordination over the new alternative is crucial to unlock *lock-ins*, and the switch to a new alternative is easier the lower are the critical mass thresholds required to induce migration of users from one technology or product to the other. Andreozzi (2004) adjusts and complements Witt's view including the feature of compatibility between technologies, suggesting that "the selection process will favor not so much efficient technologies, but rather technologies that are compatible with the already established alternative" (Andreozzi, 2004). This line of

argumentation can be linked with the literature on niches management and system transition (Schot and Geels, 2007) that posits that emerging technologies can be nurtured in closed market niches before becoming able to play a transformative role in the economic system. The issue of compatibility (or recombination) brought forward by Andreozzi is discussed, in a different context, by Bresnahan (2012) when analyzing the possible patterns leading to the emergence of general purpose technologies. Although not explicitly mentioning *lock-in*, the literature on general purpose technologies explores a rather similar territory: that of coordination and allocation failures in the making of a pervasive and dominant technology. According to Bresnahan (2012), a novel technology whose expected value, if considered in isolation, is not worth the cost of inventing it, can become viable if combined with other general purpose or specific technologies. However, the returns expected from the recombination depend, besides contractual arrangements (e.g. with respect to intellectual property rights), on the degree of entrepreneurial and market knowledge, that is the knowledge available to the single inventors and the one that can be captured on the market. From a path dependence and *lock-in* perspective, given enough knowledge available, the possibility of recombining innovations may ease the emergence of a novel alternative capable to build, in the words of Witt (1997) a critical mass of consumers. Recombination of novelties can therefore create the conditions for *lock-in* breakup; by opening the way for the establishment of a new dominant general purpose technology, however, such process also induces the generation of new locked-in trajectories of technological development.

Loch and Huberman (1999) also suggest the possibility of *lock-in* breakup; their model describes the competition between an old and a new technology in a setting featuring performance improvements (learning) and network effects generated by the size of the user base. Potential adopters of the new technology evaluate its performance at discrete intervals and decide if to switch or not. The jump from one fixed point of the system to the other

(dominance of the old or the new alternative) – that the authors interpret as a case of 'punctuated equilibria' (Mokyr, 1990) – depends on the values of the parameters modeling learning and network effects and, also, on users expectations regarding the technologies performance; furthermore user heterogeneity with respect to technology evaluation is present and plays a role in determining punctuated equilibria, stressing once again the fact that the distribution of user characteristics can affect *lock-in*. Cantner and Vannuccini (2016) argue in a similar direction; they represent technological competition in the case of vertical relationships between upstream technologies and a continuum of downstream (user) industries/applications. Given the distribution of comparative (relative) costs and benefits of adoption of an established and a new upstream technology over the continuum of downstream industries, and given the laws of motions of such relations (that are affected both by network effects and by the resistance of the established technology) the authors identify the constellations under which the established upstream technology maintains its dominance – thus, the system is locked-in in the old alternative – and those that lead the new upstream technology to 'acquire purposes' and penetrate the downstream market.

Finally, Marengo and Zeppini (2016) propose a variant of the Polya urn scheme that allows for the 'arrival of the new', namely for the entry of new competing alternatives. Their model is able to combine the role of innovation without abandoning the very analytical framework supposed to lead to inflexible outcomes. The reason identified here for the occurrence of *lock-ins* is the 'closed world' nature of the urn model; in their setting, one of the balls usually composing the urn setting acts as a 'mutator' that, once selected, introduces a new variant of choice (e.g. a new color) in the game. In a sense, innovation continuously reshuffles the cards on the desk of path-dependent processes. The idea behind this approach is represented also in models not directly interested in *lock-in*, but that illustrate similar dynamics. For example, Silverberg and Lehnert (1993) use a Lotka-Volterra predator-prey setting, adapted to model

economic cycles and the run-up between wage rate and employment rate in the style of Goodwin (1982) and enriched with evolutionary features (the same replicator dynamics as used in this contribution) to illustrate the competition between capital vintages (techniques) in an economy and how this produces fluctuations comparable to the Long Waves well known to Schumpeterian economists (Freeman and Louçã, 2001). The dynamic behavior of the system is rejuvenated at random intervals by the arrival of new techniques that restore the competition for market dominance among the competing vintages, spur a new long wave in the evolution of macro prices (unemployment rate, wages) and, in a sense, breaks tendencies towards *lock-in*.

Unlikely *Lock-ins*: population heterogeneity

Bassanini and Dosi (2006) show formally while retaining the Polya urn modeling framework and in absence of innovation how technological domination does not always occur with probability one, even under the conditions of the Arthur model, namely unbounded increasing returns with random order of the adopters:

"Unbounded increasing returns to adoption are neither necessary nor sufficient to lead to the emergence of technological monopolies. (…) Arthur's result applies only when returns are linearly increasing and the degree of heterogeneity of agents is, in a sense, small. (…) More generally the emergence of technological monopolies depends on the nature of increasing returns and their relationship with the degree of heterogeneity of the population. Given a sufficiently high heterogeneity amongst economic agents, limit market sharing may occur even in the presence of unbounded increasing returns." (Dosi and Bassanini, 2006, p. 25-26)

Adopters' heterogeneity plays a fundamental role in keeping the system of technological competition far from monopolization. In a sense, users' heterogeneity is implied also in Witt

(1997) model, given the different behavior of the diffusion agent with respect to the other users. Shy (1996, p.799) elaborates in a similar direction in its combination of technological 'revolutions' with network externalities; he finds that "*for a given product, an improved technology will be adopted by the consumers that treat quality and network as substitutes and rejected by those who treat the two components as complements. (…) (W)hen a new technology is introduced, the market for the product splits between two types of consumers: those who treat the two components as substitutes (…) and therefore adopt the new technology; and those who treat the two components as complements (…) and do not adopt the new technology*." Here, heterogeneity is defined in terms of user preferences with respect to product quality or network size; already this basic distinction generates patterns of adoption that can contrast the technological monopolization implicit in path-dependent processes and *lock-in* outcomes.

Unlikely *Lock-ins*: Degrees of path dependence

The idea that *lock-ins* are inescapable structural equilibria has spurred an extensive debate on the real-world implication of path dependence, increasing returns, feedbacks, and *lock-in* itself. Liebowitz and Margolis (1995) were among the first to point out how the theoretical definition of path dependence rests on shaky grounds, and that its empirical counterpart does not make a good job in supporting the theory. To support their claim, they distinguish between first, second and third-degree path dependence. First-degree path dependence is one under which 'sensitivity' to initial conditions does exist, but that generates no harm to the process' efficient unfolding. Second-degree path dependence generates outcomes that are inefficient *ex post*, but that were not foreseeable ex ante, due to uncertainty and limited knowledge of alternative paths and their related wealth gains. Therefore, they cannot be considered real inferior outcomes. Finally, third-degree path dependence is a form of sensitivity to initial conditions leading to inefficient outcomes that were instead avoidable *ex*

ante. While the case of third-degree path dependence implies that, at least theoretically, cases of selection of inferior alternatives may occur, the distinction between different degrees of path dependence suggests that the importance of the notion should be boiled down, especially for what concerns empirical relevance.

Unlikely *Lock-ins*: conception of path dependence

Finally, the most critical systematization of the conceptualization of path dependence and *lock-in* is the one provided by Page (2006). Page starts by pointing out how path dependence emerged as a common framework to explain diverse phenomena occurring in diverse fields, often unrelated or non-comparable. As we already claimed, there seems to be path dependence at work in cases that range from economic dynamics to technological evolution, from micro-level choice to the meso selection of institutions, from the patterns of regional specialization and diversification to macro persistence of shocks and stimuli. However, there may be several identifiable forms of history dependence. Page distinguishes between "*path dependence*, where the path of previous outcomes matters, *state dependence* where the paths can be partitioned into a finite number of states which contain all relevant information, and (…) *phat dependence* where the events in the path matter, but not their order (…) between early and recent path dependence, and perhaps most importantly, between processes in which *outcomes* are history-dependent and those in which the *equilibria* depend on history." (Page, 2006, p. 89) The label 'phat' is a clever choice of Page to define processes dependent on a whole history, but not on the sequential order of choice: the word 'phat' appears quite similar to 'path', thus suggesting a retaining of the broader meaning and structure of the process, but swaps the order of the letters, thus suggesting that the order of choices does not matter, as instead it does for path dependence. As in Dosi and Bassanini (2006), increasing returns are found to be not a sufficient condition for path dependence and *lock-in* to occur or persist, as all the competing alternatives might be showing increasing returns. Most importantly, the

focus on increasing returns detracts the attention from what is the true cause of path dependence, namely *negative feedbacks* and constraints in the not chosen alternatives. By proposing a series of variants of the Polya urn process, Page shows the inner complexity of historical dependent processes, of which path dependence is just one case. In fact, the literature on path dependence tends to conflate concepts that from a formal viewpoint describe different phenomena, for example path dependent outcomes and path dependent equilibria, where the first notion indicates that the outcome in a period depends on past outcomes, while the second describes a process in which the long-run (limiting) distribution over outcomes depends on past outcomes. Similarly, another misunderstanding is the one between early path dependence and sensitivity to initial conditions. The latter concept is usually mentioned in the literature; it is a deterministic concept that describes how the equilibrium of a system is determined by the initial conditions. However, the consensus conceptualization of path dependence and *lock-in* is stochastic in nature. More appropriate is the concept of early path dependence, where early accidents shape the probability distribution of future histories. More importantly, many of the processes of competition studied and reported as path dependent do not necessarily have to be path dependent, but only phat dependent. In those cases, the history of choices still matters, but their order does not.

To sum up, the initial idea of inescapable *lock-in* can be questioned from many perspectives: first, path dependent and phat dependent processes are stochastic, rather than deterministic – meaning the convergence is towards limiting distribution of outcomes rather than towards specific outcomes; second, increasing returns and positive feedbacks may not be sufficient to generate *lock-ins*, especially if all the alternatives are experiencing them; third, the heterogeneity of agents – namely the existence of diffusion agents willing to nurture a critical mass, or a distribution of preferences between technological performance (or product quality) and network effects – can produce outcomes other than monopolization; fourth, the arrival of

new alternatives – that is, innovation – can continuously refresh technological competition and provide a way out from *lock-ins*. From our overview, the lesson to take home is that *lock-in* meant as monopolization outcome of technological competition or incontestability of a dominant alternative is a transitory rather than a permanent phenomenon. This, however, does not reduce its relevance for policy or the fact that the notion contributes to a needed historical and evolutionary view of economic and technological dynamics. We proceed now to explore the argument mentioned before according to which negative feedbacks are a fundamental determinant of the outcomes of history-dependent processes.

4. *Lock-in*: a Neo-Schumpeterian illustration

In this Section, we employ the replicator dynamics model to illustrate in a simple, dynamic and non-stochastic setting how the (inevitable) outcome of *lock-in* can be overcome (or reinforced) by innovation, meant here not as the entry of novel alternatives, but as progressive improvements of the 'merit' – value, or performance – of the competing alternatives. We explore the respective dynamics of shares allocation and reallocation in a Neo-Schumpeterian perspective. While the replicator model has been used in Neo-Schumpeterian economics mostly to study the competition for the market (Metcalfe, 1994; Cantner, 2009; Cantner et al., 2012) between firms, we consider it flexible enough to capture the essence of the competing technologies problem. Indeed, as already mentioned, also the model of Silverberg and Lehnert (1993) does exactly that, adapting the replicator dynamics to model the competition between capital vintages, which in turn correspond to techniques active into the economy. Furthermore, it has been suggested (Dosi et al., 2015, p.16) that, from the mathematical viewpoint, the stochastic version of the replicator dynamics is equivalent to a generalized Polya urn scheme; that supports our choice to employ the replicator dynamics in order to capture some feature of history-dependent processes of technological competition.

In a nutshell, the replicator dynamics compares the 'fitness' of a given technology with that of its reference population, as it relies on the philosophy of 'population thinking' (Metcalfe, 2008). Doing that, the model adapts to the economic realm the Darwinian natural selection, or the principle of the 'survival of the fittest'. In the literature, the fitness f of one technology, or firm, or agent, is usually represented by a proxy whose rationale is sound from the viewpoint of economic thinking: unit cost, productivity, product quality are examples in this sense. The fitness of the population $\bar{f}$, in turn, is represented by the share-weighted average fitness of all the agents active in the market, industry, or environment of interest (thus we have $\bar{f} = \sum_i s_i f_i$, where i indexes the alternatives, and s tracks the share of each alternative in a given period – we dropped the time index t for simplicity). Hence, the standard replicator equation, that takes the form $\dot{s}_i = s_i \lambda (f_i - \bar{f})$ describes the change of the frequency (share) of each actor (represented by a dotted variable in the continuous case – formally it is the derivative of an agent's market share with respect to time) as a function of the relation (positive or negative) between her fitness and that of the reference population. The parameter λ is usually called 'speed of selection' and captures the efficiency through which the advantage (disadvantage) of having a superior (inferior) fitness translates in gains (losses) of shares.

While empirical tests of selection return at best ambiguous results (Cantner et al., 2016), the replicator model remains a useful tool to study the conditions under which monopolization occurs. In fact, different scenarios of competition for the market can be explored (Mazzucato, 1998). In its simplest formulation, actors have fixed fitnesses, there is no entry or exit (in a way similar to the 'virgin market condition' setup criticized by Witt) of alternatives and what drives the dynamics of the system is only the continuous reallocation of shares to alternatives that have higher fitness, which in turns changes the level of the share-weighted average

fitness. The necessary outcome under this setting is monopolization – *lock-in*. The speed of transition to *lock-in* depends on initial conditions (the distribution of market shares at the setup of the model) and on the speed of selection λ (that helps to calibrate the model to the specificities of different contexts), but the outcome is unsurprising: the fittest survives. The dynamics is only driven by *positive feedbacks* in the selection process, in the sense that the average fitness $\bar{f}$ is changing step by step in favor of the (in the end) dominating alternative respectively impairing the inferior alternative. Figure 1 plots as an example the evolution of market shares for five technologies when the fitness is the (negative) unit cost under the conditions just described: shortly after $t = 100$ the system locks-in around technology one, the one with the highest fitness since the very beginning.

Figure 1 about here

However, the essence of path dependence and *lock-in* is that 'inferior' outcomes can prevail due to stochastic shocks intervening along history; contrariwise, the simulation just shown indicates that *lock-in* happens, but always favoring the superior alternative. An extended replicator model should, therefore, account for more elaborated forms of competition, where also inferior alternatives can become uncontestable. In this case, the issues at stake become two: if the prevalence of inferior outcomes occurs, and if such outcome is inescapable.

Mazzucato (1998) introduces the possibility for competing alternatives to improve their fitness by engaging in innovative activities under different scale returns scenarios. This introduces an additional (positive or negative) feedback mechanism into the competition, in form of (different types of) returns to scale acting as improvements at the level of the individual fitness, being the result of innovation. The two feedback mechanisms, one via selection and the other via innovation, interact either by reinforcing or by dampening each

other. Formally, individual improvements are modeled relating the changes in fitness to the current share owned by an alternative. In the generic case, the laws of motion read as follows:

$$\dot{f} = \gamma f_i, \text{ for constant returns}$$

$$\dot{f} = \gamma f_i s_i, \text{ for increasing returns (positive feedbacks of share to fitness), and}$$

$$\dot{f} = \gamma f_i (1 - s_i), \text{ for decreasing returns (negative feedbacks of share to fitness),}$$

where γ is a parameter assumed to be uniform across all actors that captures exogenous improvements. From an innovation viewpoint, what we introduced here is process innovation, rather than product innovation; while product innovation – or 'the arrival of the new', as discussed in Section three – modifies the set of alternatives, process innovation affects the value/fitness of the alternatives. Superiority or inferiority as meant in the *lock-in* literature is therefore treated as a variable rather than as a parameter (that is, a given feature of the technology), and it is endogenously determined by the model. Constant and increasing dynamics returns reinforce the selection dynamics and hence the speed of arriving at a *lock-in*, while decreasing dynamics returns provide the most interesting result for the objective of this Chapter, where continuous catching-up and leap-frogging taking place between the dominant alternative and the competing ones. Figure 2 shows the dynamic allocation problem under decreasing returns. In the example provided, after enough time, monopolization does not occur, and the system stabilizes far from the corner solutions implied by *lock-in*.

Figure 2 about here

As already suggested by Page (2006), a competition between alternatives all characterized by increasing returns may not display *lock-ins*. Decreasing returns are in this sense a more interesting case provided by the replicator model. The interaction of negative feedbacks at the

level of the individual alternative and selection (with positive feedbacks) going in the opposite direction constrain the wannabe-dominant alternatives as soon as they get close to becoming uncontestable. While for Page negative feedbacks are meant as bounds trapping some alternatives and leaving room open for dominance to those less affected by decreasing returns, the replicator dynamics tells a somehow different story: negative feedbacks moderate selection and lead to (at least early) instability and uncertainty over the winner of the race to dominance among alternatives. *Lock-in* in presence of negative feedbacks, even without the 'arrival of the new', might not be inescapable after all.

The replicator model can be used to include additional elements among those highlighted in our literature review. For example, the compatibility issue raised by Andreozzi (2004) can be added to the replicator setting by modeling a chain of connected technologies. Cantner et al. (2016) explore this possibility, however with a different aim: to capture the effect of value chains relations on selection dynamics. Despite different premises, however, the phenomena under analysis are structurally rather similar, and the findings may hold as well: the existence of a chain of compatible and interdependent components (that is, a complex technology meant as a near-decomposable and hierarchical architecture of sub-technologies) – especially when components are matched randomly – can produce at the same time the success of inferior alternatives (as path dependence studies suggests) and an even stronger turbulence in technological competition, with continuous takeover of leadership.

With respect to the aims of this Chapter, however, our claim is that the replicator dynamics can be a useful tool to study how *lock-in* emerges and can be escaped under different regimes of competition between alternatives. What this kind of models shows is that scholars have just started to scratch the surface of the complex dynamics leading to inflexible outcomes. Other classes of models, for example percolation models of technological diffusion (Silverberg and Verspagen, 2005), in which a technology diffuses by 'percolating' through a lattice or

landscape, endogenously activating always new areas willing to adopt it, in a cascade-like process, may further enrich our understanding of the processes leading (or not) to *lock-in*.

5. Conclusion

In this Chapter, we provided a peculiar vision of *lock-in* and path-dependent processes. Our contribution has been that to incorporate recent critiques to the conceptualization of history dependent dynamics as they are employed so far to explain cases of (technological) competition that may be affected by small historical events. While *lock-in* is conceptually considered as an inescapable outcome, we argued in the opposite direction: critical literature highlighted how innovation, diffusion agents achieving critical masses of adopters, responses of established/dominant technologies and adopters' heterogeneity may keep the dynamical problem of allocation between alternatives far from monopolization and locked-in situations of rest. We employed the replicator dynamics model – a modeling strategy alternative to the standard Polya urn setting used in *lock-in*-related literature, that however retains its mathematical properties – to reinforce the claims about the absolute inflexibility of *lock-ins*, and suggested that negative feedbacks, when combined with selection processes displaying positive reinforcement, may play a pivotal role in influencing dynamic allocation problems among alternatives. In sum, it seems that *lock-in* is not always inescapable, and policy should be aware of this property of history-dependent processes in order to design intervention in a more 'catalytic' manner (Cantner, 2015; Cantner and Vannuccini 2012). More precisely, Research and Innovation policies designed to focus on the direction, rather than on the rate of innovative activities, should create protected arenas for 'experimentation' of technologies before and next to the main arena of the market. Furthermore, policy support to one or the other technological trajectory has to acknowledge what has been suggested earlier on with respect to competition between complex, system and platform technologies, where outcomes

of prevalence have to be assessed considering their compositional nature, with history-dependent processes running at the level of components/sub-systems and aggregating up to the level of the technology of interest. The latter point highlights also what could be a promising research avenue in the ambit of history-dependent processes: to elaborate a generalized theory including the factors discussed in this Chapter: heterogeneity of adopters, complexity of the technology, nested path and phat dependence.

Finally, the Chapter was also meant to provide an answer to the question if *lock-in* is a well-defined concept at all. Building on our claims at the end of Section 3, our tentative reply is that, in the universe of real-world technological competition, where the 'virgin market condition' is only an ideal-type and complex, multi-dimensional and multi-level interactions take place, *lock-in* meant as inflexibility of outcomes is predominantly a transient, rather than an equilibrium property. *Lock-in* may not be an ill-defined concept, but it relies on an ill-defined understanding of history-dependent processes that should be amended by economists and scholars of technological change in the direction of a theory of flexible, rather than inflexible, outcomes.

The fact that processes of allocation of choices, resources, and market shares between alternatives might not end up trapped forever in inferior outcomes despite the existence of non-constant returns does not imply that transitory effects of path and phat dependence do not require corrective measures at all. After all, economic life is what happens in the transition between (temporary – due to innovation) fixed points.

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Fig 1. Replicator Dynamics with 5 competing technologies and fixed fitness.

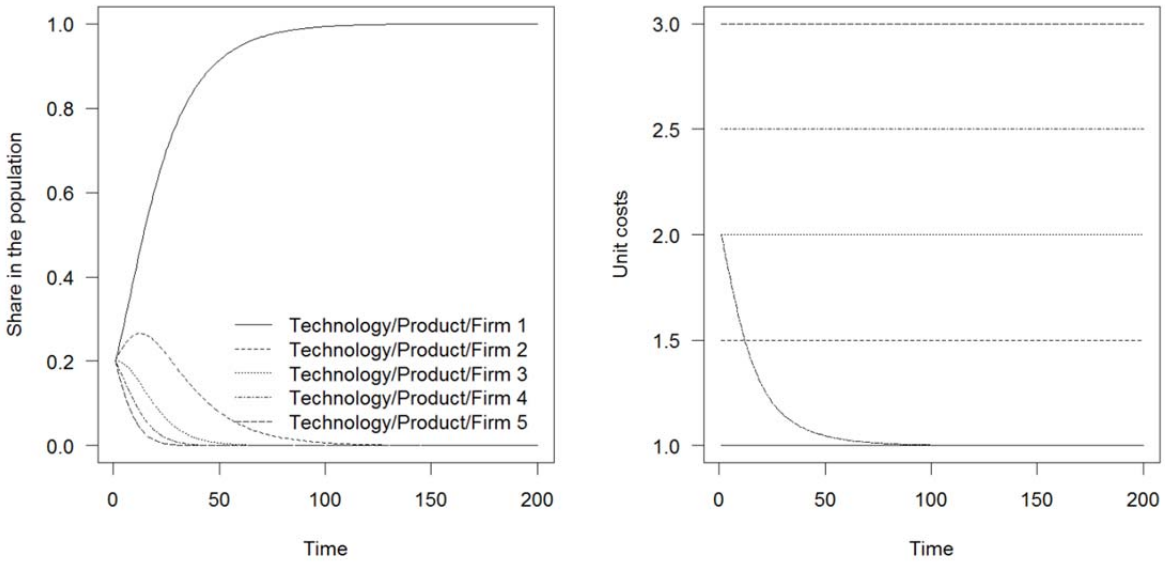

Fig 2. Replicator Dynamics with two competing technologies and negative feedbacks