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POINT COUNTERPOINT

The Missing Link Between the Theory and Empirics of Path Dependence: Conceptual Clarification, Testability Issue, and Methodological Implications

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ABSTRACT Path dependence is a central construct in organizational research, used to describe a mechanism that connects the past and the future in an abstract way. However, across institutional, technology, and strategy literatures, it remains unclear why path dependence sometimes occurs and sometimes not, why it sometimes lead to inefficient outcomes and sometimes not, how it differs from mere increasing returns, and how scholars can empirically support their claims on path dependence. Hence, path dependence is not yet a theory since it does not causally relate identified variables in a systematized manner. Instead, the existing literature tends to conflate path dependence as a process (i.e. history unfolding in a self-reinforcing manner) and as an outcome (i.e. a persisting state of the world with specific properties, called 'lock-in'). This paper contributes theoretically and methodologically to tackling these issues by: (1) providing a formal definition of path dependence that disentangles process and outcome, and identifies the necessary conditions for path dependence; (2) distinguishing clearly between path dependence and other 'history matters' kinds of mechanisms; and (3) specifying the missing link between theoretical and empirical path dependence. In particular, we suggest moving away from historical case studies of supposedly path-dependent processes to focus on more controlled research designs such as simulations, experiments, and counterfactual investigation.

INTRODUCTION

Broadly speaking, path dependence is about increasingly constrained processes that cannot easily be escaped. As already noted by Sydow et al. (2009), path dependence has become an essential theoretical construct for many organization scholars. A database search in seven leading organization and management journals for the period 1998–2007 shows that the notion of path dependence becomes more and more popular. Between 1998 and 2002, 109 articles published in *Academy of Management Journal*, *Academy of Management Review*, *Administrative Science Quarterly*, *Journal of Management*

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Studies, *Organization Science*, *Organization Studies*, and *Strategic Management Journal* make a direct reference to path dependence, path dependency, or path-dependent processes. This accounts for 6.15 per cent of all papers published in these journals. Between 2003 and 2007, the figure increases to 214 articles, i.e. 10.5 per cent of all articles published. Despite the common use of the construct in scientific publications, a number of scholars note that no clear definition of path dependence is shared within the scholarly community (Djelic and Quack, 2007; Morgan and Kubo, 2005; Pierson, 2000). Indeed, it is hard to tell what constitutes acceptable empirical evidence for path dependence. Some scholars remain sceptical about the empirical support for path dependence (Liebowitz and Margolis, 1990), while others go as far as to wonder whether 'path dependence operates in the real world . . . or whether it is purely a theoretical artifact' (Hirsch and Gillespie, 2001, p. 72; see also Ekelund and Tollison, 1997, p. 387; Liebowitz and Margolis, 1994).

We believe it is time to take stock of past research and analyse carefully the theoretical and empirical underpinnings of path dependence. It should appear problematic to the scholarly community that one published article in ten refers to a blurry and controversial construct. Thus, this paper proposes to critically review the use of path dependence at three levels of analysis. At the macro level, institutionalists use path dependence to account for (harmful) institutional persistence (Djelic and Quack, 2007; Mahoney, 2000; Morgan and Kubo, 2005; North, 1990; Pierson, 2000; Thelen, 1999). At the meso level, economists rely on path dependence to explain suboptimal governance or technology outcomes (Arthur, 1989, 1990; Cowan, 1990; David, 1985; Gedajlovic et al., 2004; Williamson, 1999). At the micro level, the dynamic capability view refers to path dependence as a surrogate for organizational rigidity while paradoxically insisting on its positive impact on competitive advantage (Eisenhardt and Martin, 2000; Helfat and Peteraf, 2003; Schreyögg and Kliesch-Eberl, 2007; Sydow et al., 2009; Teece, 2007; Teece et al., 1994, 1997; Vergne and Durand, 2010).

In contrast with past organizational research, we offer a narrow definition of path dependence as a property* of a stochastic* process which obtains under two conditions (contingency* and self-reinforcement*) and causes lock-in* in the absence of exogenous shock.[1] According to this definition, path dependence ceases to be a ubiquitous construct describing most historical sequences. Instead, we privilege explanatory power: our definition of path dependence is thus applicable to a restricted set of sequences, but with a greater theoretical and empirical value. We take a step further by discussing the missing link between the theory and empirics of path dependence. Important issues have prevented scholars from testing path dependence empirically in an adequate way. Our redefinition emphasizes the two conditions necessary to obtain path dependence, and to clearly distinguish it from other 'history matters' kinds of theoretical constructs. Because a necessary condition* of path dependence, namely contingency, is practically impossible to verify* or falsify* in case study research (Bassanini and Dosi, 2001; David, 1985; Foray, 1997), and because misleading claims about suboptimality* threaten the validity of path dependence research (Goldstone, 1998; Hirsch and Gillespie, 2001; Liebowitz and Margolis, 1990, 1995), we recommend using highly-controlled methodologies in the future to develop more robust path dependence research (i.e. simulation, experiment, counterfactual modelling).

PATH DEPENDENCE AT THE MACRO, MESO, AND MICRO LEVELS

Past research in organization science demonstrates that we can do without the notion of path dependence to understand that 'history matters'. For example, we know that what managers learn today influences what they will be able to learn tomorrow as absorptive capacity increases (Cohen and Levinthal, 1990). Where investments are made now is likely to constrain where they can be made in the future (Dierickx and Cool, 1989). Under certain conditions, firms that move first will gain a sustained advantage over their competitors (Lieberman and Montgomery, 1988). Institutions tend to evolve incrementally rather than radically, so yesterday's rules of the game are often very similar to today's rules (Scott, 1995; Selznick, 1957). Organizational characteristics tend to reflect how things were at the time of organizational founding (Marquis, 2003; Stinchcombe, 1965). Most organizations display inert structures, as if their past history determined their present state (Hannan and Freeman, 1984). Absorptive capacity, first-mover advantage, institutional persistence, imprinting, or structural inertia are all well-known theoretical mechanisms that explain how certain aspects of the past relate to current properties of organizations. Path dependence, too, proposes to connect the past and the present in a formal way, at the (macro) level of institutions, at the (meso) level of technology and governance modes, and at the (micro) level of organizational resources and capabilities.

The Macro Level: Institutions

Path dependence scholars view institutions as 'carriers of history' which maintain existing behavioural norms and cultural patterns throughout time (David, 1994). From an institutional perspective, the interest of path dependence seems to reside in the potential 'inefficiency of history' (March and Olsen, 1989) that results from the stickiness of institutions. North maintains that 'once an economy is on an "inefficient" path . . . it can persist because of the nature of path dependence' (North, 1993, p. 3). For example, organizations that strive within a given institutional matrix have a stake in perpetuating the 'rules of the game' that favour their own survival, even when such rules are globally inefficient, thereby hampering institutional change (North, 1990; Pierson, 2000). Although institutional scholars traditionally associate path dependence with an absence of change leading to persisting inefficiencies, a more recent view shifts the focus from unproductive status quo to novelty. As Garud and Karnøe put it, '*novelty* . . . is not a negation of the past, but an elaboration and extension in specific directions depending on the particular sequence of unfolding events. Stated differently, the emergence of novelty is a path dependent phenomenon' (Garud and Karnøe, 2001a, p. 1). While this definition enriches the institutional perspective on entrepreneurship (e.g. Garud, 2008), it also broadens the list of possible outcomes of path dependence to encompass innovation in addition to persistence (see also Garud et al., 2010; Porac et al., 2001). Surprisingly, the same mechanism – path dependence – could explain either the persistence of existing (and possibly inefficient) institutions, or the creation of new ones. Innovation is certainly about recombining previous knowledge (Kogut and Zander, 1992), and is thus *past*-dependent, yet path dependence goes beyond the mere idea that the past channels future opportunities.

Furthermore, if we define institutions as stable social patterns and identify path dependence with persistence, as is usually the case, then is it not tautological to speak of path-dependent institutions? If not, what does path dependence add to the standard characterization of institutions? A way to clarify the debate is to clearly distinguish between the process of path dependence (which, we will show, consists of contingency and self-reinforcement) and its outcome (a specific state of persistence called lock-in). This distinction is helpful because it makes visible the divide between path dependence scholars who accept the contingency assumption and those who doubt its relevance. For example, several researchers (Garud and Karnøe, 2001b; Rao and Singh, 2001; Sydow et al., 2009) reject the idea that novel paths emerge serendipitously, that is, they deny the role of accidental events in path origination to focus instead on human agency, while others insist that small contingent events are necessary to distinguish path dependence from the mere action of institutional increasing returns*, sunk costs, or adaptive expectations (Arthur, 1989; David, 1985; Goldstone, 1998; North, 1990; Schwartz, 2004). Accordingly, such mechanisms would contribute to path dependence only as amplifiers of 'small events and chance circumstances', identified as the true origin of paths (North, 1990, p. 94; see also Arthur, 1989; David, 1985).

Thus, the usefulness of path dependence is bound to remain limited if it explains both persistence and its opposite (i.e. novelty); path dependence may even be tautological, or superfluous relative to existing theories, as we will further discuss in the following.

The Meso Level: Technology and Governance

At the meso-level, the definition of path dependence suffers from the same ambiguities. Path dependence often appears to be a quasi-synonym of persistence. Helfat (1994, p. 1722) sees 'persistence in R&D as an example of a wider phenomenon termed "path dependence" '. Cowan and Gunby (1996, p. 521) speak of technological inertia caused by increasing returns to explain why certain paths have 'a tendency to become entrenched'. In their case study of pest control strategies, the two authors maintain that path dependence induces persisting inefficiencies at the technology level. Similar claims, all based on historical case studies, have been made about the technological development of keyboards (David, 1985), nuclear power reactors (Cowan, 1990), or videocassette recorders (Arthur, 1990). The overarching logics behind technological path dependence is grounded in the fact that repeated R&D investment creates sunk costs, which result in irreversibilities along the path of technology development (David, 1985; Helfat, 1994).

At the level of organizational governance, path dependence is also recognized as a serious issue which can account for persisting inferior governance structures (Williamson, 1999). For example, Gedajlovic et al. (2004, p. 900) argue that 'path dependencies . . . inhibit the transformation' of founder- into professional-managed firms. Repeated patterns of investment in human or material resources lead to routine creation and asset specificity, which both introduce stickiness at the governance level and prevent subsequent adjustment (Gedajlovic et al., 2004; Williamson, 1999).

Broadly speaking, when it comes to technology development or governance structures, path dependence is used in the literature to describe any meso-level process involving

capital or asset accumulation. As was already the case in the institutional literature, the outcome of such processes can, but need not lead to suboptimal outcomes (Cowan and Gunby, 1996; David, 1994). The existing literature gives little guidance to understand what determines the nature of outcomes (e.g. persistence or change) and their properties (e.g. suboptimal or not). Liebowitz and Margolis (1995) remark that if path dependence simply means that investment decisions sometimes appear inefficient *ex post* when new information is revealed, then path dependence is nothing but an intertemporal propagation of error caused by information incompleteness. That is, the notion of incomplete information better captures temporary irreversibility in investment sequences than path dependence does. The persisting indeterminacy in the conceptualization of path dependence raises the issue of whether the construct is theoretically distinctive, and what it adds as a conceptual mechanism explaining institutional, technological, and strategy persistence.

The Micro Level: Firm Resource and Capability

At the resource and capability level, path dependence is a central concept to the resource-based view (RBV) and the dynamic capability view (DCV) (Eisenhardt and Martin, 2000; Helfat and Peteraf, 2003; Schreyögg and Kliesch-Eberl, 2007; Teece, 2007; Teece et al., 1997). Strategic management scholars associate path dependence with the kind of persistence caused by repeated investment in firm resources and capabilities, which can create competitive advantage (Barney, 1991; Dierickx and Cool, 1989; Teece, 2007) but also rigidities and harmful lock-in (Leonard-Barton, 1992; Teece et al., 1997; Tripsas, 1997). Specifically, the outcome of path-dependent capability development is more likely to be positive for the firm when asset complementarities, learning specialization, or increasing returns to scale and scope prevent imitation by its competitors. As Helfat and colleagues put it, the 'idea that capabilities emerge from a series of path-dependent learning experiences is a central one. Further, competitive advantage requires that these capabilities are valued by customers, and are difficult to imitate by competitors' (Helfat et al., 2007, pp. 62–3).

Paradoxically, while capability development is path-dependent, the role of dynamic capabilities is to 'purposefully create, extend, or modify [the firm's] resource base' (Helfat et al., 2007, p. 1) to increase environmental fitness and avoid lock-in. At a theoretical level, dynamic capabilities emphasize the managerial ability to orchestrate a firm's assets so as to avoid harmful inertia in a rapidly changing environment (Teece et al., 1997). It follows that dynamic capabilities are construed simultaneously as path-dependent and as a remedy to path dependence. Because of this ambiguity, the capability lifecycle framework describes path-dependent capability trajectories but fails to specify when path dependence will lead to capability retirement, replication, or recombination (Helfat and Peteraf, 2003).

At the micro-level, it remains unclear how exactly path dependence differs from resource accumulation or capability building (i.e. persistence of a micro-organizational pattern). Again, the definition appears too broad because it does not sufficiently exploit two distinctive conditions for path dependence: contingency and self-reinforcement. Does it make sense to speak of path dependence leaving aside the 'chance events [that]

may cause "lock-in" on inferior technologies', and that explain why 'companies with the best products will not always win' (Teece et al., 1997, p. 523)? If we agree that most investments in resources and capabilities are carefully thought through, then we should be able to propose a distinctive definition of path dependence that attributes correctly to a given outcome (success or failure) its antecedents by reconsidering the causal powers of 'chance events' relative to resource/capability properties. By the same token, we should be able to dissociate accumulation from other self-reinforcing mechanisms to better define path dependence and avoid theoretical confusion (Vergne and Durand, 2010).

WHAT IS PATH DEPENDENCE, REALLY, AND (WHY) DOES IT MATTER?

We define path dependence as a property of a stochastic process which obtains under two conditions (contingency and self-reinforcement) and causes lock-in in the absence of exogenous shock. Because it has formal theoretical roots in the mathematics of Markov chains (see Appendix 1), path dependence should not become an umbrella category for all theories that explain why institutions, technological standards, or firm capabilities tend to persist over time. Table I presents several alternative theories according to which 'history matters', and shows how they differ from path dependence along several features (initial conditions, triggering event, sustaining mechanism, level of analysis, outcome, and degree of outcome probability). There lies the theoretical interest of path dependence: *if we accept to narrow down its definition to its logical core, and recognize that not every historical process is path-dependent, it can explain phenomena that other theories cannot.*

History Unfolding: Two Conditions for Path Dependence

Condition 1. Contingency. What triggers path dependence is still unclear in the literature. While some scholars associate path dependence with sensitive dependence on initial conditions (Baum and Silverman, 2001; Liebowitz and Margolis, 1995), Goldstone (1998, p. 834) maintains that path-dependent outcomes are '*not determined* by any particular set of initial conditions'. In fact, path dependence occurs when initial conditions are followed by a series of contingent (or chance) events whose influence on the path taken is larger than that of the initial conditions themselves. Consistent with prior works, by contingent we mean unpredictable, non-purposive, and somewhat random events (Arthur, 1989; De Rond and Thietart, 2007). For instance, a first mover advantage is rarely contingent: firms strategically plan to enter first in markets when they know it can be beneficial. Therefore, a persisting market domination explained by first mover advantage would not qualify for a path dependence explanation.[2]

The existence of contingency in organizational life is a reasonable assumption. Kenney and von Burg describe the 'good fortune at play in luring [William] Shockley back to Palo Alto' in the early 1950s (Kenney and von Burg, 2001, pp. 137–8). The co-inventor of the transistor could not find investors on the East Coast, where potential government applications for his research would have found a natural niche, so he had to

Table I. Path dependence and other 'history matters' notions

Theoretical argument	*Influence of initial conditions*	*Triggering event*	*Sustaining mechanism*	*Level of analysis*	*Outcome*	*Degree of outcome predictability*	*Representative works*
Path dependence	Very weak	Contingent events	Self-reinforcement	Multiple (scalability)	Lock-in	Very low *ex ante;* medium as self-reinforcement starts	Arthur (1989); David (2001)
Absorptive capacity	Weak	Knowledge stock	Knowledge flows	Group: organization	Innovation, performance	Medium (depends on market demand and competition)	Cohen and Levinthal (1990)
Institutional persistence	Strong	N/A	Stickiness of institutional patterns at a socio-cognitive level; isomorphism	Institution	Institutional stability; incremental change	Important in absence of exogenous shocks	North (1990); Selznick (1949); Scott (1991)
Resource accumulation	Strong (managerial commitment)	Managerial decision	Repeated commitment	Resource, capability	Uniqueness, non-replicability	High	Helfat (1994); Dierickx and Cool (1989)
Structural inertia	Strong	Firm founding	Accountability, reliability	Environment/ organization	Increased firm survival (early in the process)	Medium to high (depends on firm environment)	Hannan and Freeman (1984)
Imprinting	Very strong	Date and place of founding	Institutionalization	Organization	Persistence of firm structural properties	Medium to high (depends on firm environment)	Stinchcombe (1965); Marquis (2003)
First-mover advantage	Very strong	Order of entry	Entry barriers, pre-emption of scarce resources	Organization-market	Market predominance	Low to medium (depends on rivals, industry structure and regulation)	Lieberman and Montgomery (1988)
Chaos theory	Maximal	N/A	Hyper-determinism + existence of chaotic attractor	Multiple (scalability)	Entirely determined by initial conditions	Very low	Baum and Silverman (2001); McKelvey (1999)

go back to California. There he trained eight engineers who eventually left his lab to create Fairchild Semiconductors, a company which 'catalysed the pattern of new firm formation that put the "silicon" in Silicon Valley'. Contingency in organizational life can take many shapes (e.g. unexpected encounters, trial-and-errors leading to unattended consequences) and seems to have potential for long-term effects.

Condition 2. Self-reinforcement. The unpredictability inherent to path dependence comes from the fact that, as the process unfolds, the outcome distribution changes – that is, the likelihood of obtaining a certain outcome varies with time. This is the case because path dependence is a property of processes similar to non-ergodic* Markov chains. Once a path has been contingently selected, various mechanisms can lead to its self-reinforcement, such as positive network externalities* or increasing returns (e.g. to scale, to scope, to learning) (Arthur, 1989; Bassanini and Dosi, 2001; Pierson, 2000). For example, QWERTY keyboard production becomes more and more profitable as production scale increases, because fixed costs are distributed across a larger number of units. From the user's perspective, getting accustomed to QWERTY keyboards makes typing easier and quicker, so that the more a user types on QWERTY, the more utility he/she derives from it. Production scale and user learning loops both contribute to reinforcing QWERTY as the preferred keyboard. More generally, features of self-reinforcement are very common in organizational life (Arthur, 1989).

Page (2006, p. 90) establishes that 'increasing returns are neither necessary nor sufficient for path dependence': what is really required to sustain a path is a mechanism that decreases the relative attractiveness of alternatives (Arrow, 2000; Kay, 2005). Imagine that agents have to choose between only two possible paths which both yield decreasing returns; logically, lock-in should occur on the path whose returns decrease at the lowest speed. Learning loops for QWERTY users not only make QWERTY more attractive, but also alternative keyboards less attractive, because of the time it would take to reach the typing performance of an advanced user on a new system. Thus self-reinforcement, to be effective, needs to include at least one negative externality to decrease the attractiveness of alternative paths.

Path Outcome: Lock-In

When a process possesses the property of path dependence, then lock-in will occur on one of the possible outcomes if no exogenous shock disturbs the system. Lock-in characterizes a state of equilibrium with a very low potential for endogenous change – put simply, lock-in is a hard-to-escape situation. Path dependence has a true theoretical substance that basically says: when contingently selected paths undergo self-reinforcement, then, *ceteris paribus*, lock-in will occur on one single path as alternative options are selected out (owing to negative externalities). Lock-in is a state of the system that cannot be escaped endogenously. Because paths are selected contingently, lock-in can happen on any path, i.e. not necessarily on the optimal one. Put differently, initial conditions do not determine which equilibrium will eventually prevail,[3] and path dependence potentially leads to a large diversity of outcomes owing to the stochastic*

nature of the underlying process. Formally, path-dependent processes are such that, for any set of initial conditions I, the probability of any outcome O conditioned by I verifies: $\forall(O,I)$, $P(O|I) < 1$. This theorem states that it is impossible to foresee with certainty the outcome of a path-dependent process when only its initial conditions are known.

The QWERTY case is a well-known example of alleged lock-in on a suboptimal* path. Arguably, tremendous exogenous influence would be required for the QWERTY standard to be replaced by another one (David, 1985; for a critique, see Liebowitz and Margolis, 1990). If it is correct that QWERTY was chosen contingently among alternative keyboards and is not the best keyboard, then the history of keyboard standards must have been path-dependent.

Empirical Scope and Theoretical Interest

At this stage of the paper, we have proposed a clear definition of path dependence, detailing how paths are created, how they reinforce themselves, and how they reach a state of equilibrium in the absence of exogenous shocks. While all necessary components of path dependence, taken individually, are common in organizational life, their adequate combination might be less common, so it remains unclear how often path dependence is likely to manifest itself empirically. Are stories of the QWERTY type exceptional, or do they represent a significant proportion of technological paths? Cross-national comparison in a given industry often provides interesting clues. For example, the fact that combustion engines independently emerged as a standard in all developed countries despite very different initial conditions (Foray, 1997; Foreman-Peck, 1996) should rule out, as possible explanations, both chaos theory (e.g. no hypersensitivity to initial condition) and path dependence (e.g. no outcome diversity). By contrast, when we observe outcome diversity *despite* similar initial conditions, path dependence is a serious candidate to account for differential evolutionary paths. At the institutional level, Bassanini and Dosi (2001) note that Cipolla's model of Europe's development in the modern age gives a central role to 'minor lucky events' with huge intertemporal consequences on the world's balance of power (Cipolla, 1965). At the technology level, Schreyögg and Blinn (2008) remark that dubbing in the film industry has persisted in several countries with a small cinema audience despite its large fixed cost and the existence of a better option (i.e. subtitling). At the resource and capability level, only Pfizer was lucky enough both to remark that antihypertensive drugs had side-effects on male erection and to seize the opportunity to pursue a new research path following a contingent discovery (De Rond and Thietart, 2007).[4]

LOOKING FOR THE MISSING LINK: THE EMPIRICAL TESTABILITY OF PATH DEPENDENCE

As noted by Hirsch and Gillespie (2001, p. 43), 'the proposition that "history matters" intuitively goes together with some sort of thought experiment (or counterfactual) which can be rarely undertaken through an actual experiment' (see also Durand and Vaara, 2009). Because testing path dependence involves a comparison 'between the current state of the world and what the world would now be like had a different path been

followed' (Cowan and Gunby, 1996, p. 521), it is still contested whether case studies such as QWERTY or VHS constitute acceptable empirical evidence (Liebowitz and Margolis, 1990, 1995). Drawing on epistemology, this section addresses three empirical issues that have so far precluded path dependence research to produce undisputable empirical findings. In each case, we unpack the conditions under which observable phenomena can be said to verify or falsify path dependence.

Issue 1: The Contingency Assumption – Verifiability

For the sake of simplicity, and consistent with past research (Arthur, 1989; Kay, 2005), the following discussion models path-dependent processes as adoption patterns in the broad sense: social actors adopt technologies, institutions, or develop resources, and some of these adoption paths end up dominating others (e.g. lock-in occurs). Adoption patterns can be represented as sequences of digits: for instance, when two entities A and B compete for adoption, the sequence '01101100110111100010' means that B was chosen first, then A twice, B again, etc., with 0 and 1 coding, respectively, for adoptions of B and A. Consistent with the assumption that contingent events appear random to us (Arthur, 1989; De Rond and Thietart, 2007), contingency is modelled hereafter as random events. We recur to an intuitive approach of randomness derived from the works of mathematicians (Chaitin, 1975; Li and Vitanyi, 1997; Solomonoff, 1960), according to which a series of events appears more random than others when more information is necessary to generate it (Chaitin, 1975). For instance, using computer language, the program 'Write "1" 20 times' yields a series of digits that appears less random than the output given by the instruction 'Write 01101100110111100010', for it uses a smaller algorithm (i.e. 18 characters instead of 26). This is consistent with the idea that random information is information that cannot be reduced to something simpler. This is why a human brain usually estimates that '11111111111111111111' appears less random than '01101100110111100010'.

In his adoption model, Arthur (1989) identifies the source of lock-in on technology B in the early contingent lead in B's adoptions, later reinforced by increasing returns. According to Arthur, contingency means that early in the adoption process, something like 'twenty adoptions of B in a row' occurs and gives B a definitive advantage over A. Such a statement is counter-intuitive though, since repetitive patterns are more likely to have a non-random origin, as explained above. Yet Arthur considers that such a repetition is the true chance event that triggers path dependence.

By contrast, as organization scientists, we tend to believe that the more repeated a sequence of events in a bounded time period (e.g. organizational failure, CEO dismissal), the more likely a structural explanation can account for it. This is indeed a crucial assumption on which much social science research is based. Consequently, when path dependence is invoked to explain why VHS won over Betamax on the ground that an initial lead in VHS adoptions was subsequently amplified by positive network externalities, it is essential to justify that the initial lead was contingent – and not caused by structural forces. Alternatively, if we believe that VHS gained an initial advantage over Betamax because the former offered higher customer value due to longer recording time (Liebowitz and Margolis, 1995, p. 222), or because of its 'sheer ability to deliver more

VHS machines than Beta producers could make early on in the competition' (Cusumano et al., 1992, p. 47), we should acknowledge that VHS's success is trivially explained by product quality and strategic savvy. Seen from this perspective, path dependence looks like a superfluous theoretical subtlety – hence the controversy.

To claim that something is contingent is not quite like proving it actually is. What kind of random events (i.e. not attributable to VHS's superiority as a competitor) could account for VHS's initial lead? Chaitin (1975) asserts that evidence for randomness cannot easily be produced. Going back to our simple model of adoption patterns, to show that a series of digits is random, one needs to prove that no program of a complexity smaller than that of the series exists that could generate it. According to Chaitin, Gödel's incompleteness theorem contains the rationale for why such evidence is often impossible to produce. Any formal system consisting of a formal language and a set of inference rules can be associated with a given degree of complexity. The more complex the system, the more complex the information derivable from it (e.g. theorems and their proofs). As a consequence, complex proofs cannot be established within simple systems: the information they contain is considered uncompressible and therefore appears random. This inherent limitation of formal systems leaves theoretical systems like those employed in the social sciences in an even more difficult position for proving randomness or chance. The bottom line is: organization scholars will not be able to verify path dependence empirically if their argument relies on the *ex post* demonstration that something did happen contingently.[5]

The chancy character of an adoption pattern is unlikely to ever be empirically evidenced. While chance remains a reasonable assumption in formal models where A and B only differ in their payoff structure (e.g. Arthur, 1989), in real-world situations like VHS vs. Betamax, customers adopt A or B based on their preferences and the perceived properties of A and B. A causal link certainly exists between the idiosyncratic properties of a technology (e.g. design, technical specifications, brand reputation) and the decision to adopt it. Thus in empirical studies, the chance argument is no more provable than in formal models, but it is even less realistic since human agents are not assumed to behave randomly. In other words, the verifiability of contingency, a necessary condition for path dependence, remains a serious issue.

Issue 2: The Contingency Assumption – Falsifiability

One may wonder how it can be argued that VHS's early advantage is due to *something else* than chance, that is, how the contingency assumption can be falsified. Suppose that A and B stand for two entities competing for adoption, and whose payoff structures are hard to compare early in the process. In order to disconfirm empirically the path-dependent explanation based on contingency, one needs to show that B possesses at least one property that differs from A's which could explain why B got adopted. A and B certainly differ in at least one of their respective properties: if they did not, then A and B would not be distinct.[6]

To falsify contingency, it is necessary to assume that there exist property differences between A and B that could capture variance in adoption trends. Yet, relating both actors' preferences and property differences to the adoption pattern is a considerable

challenge: extensive data about the adopters' and promoters' motivations needs to be gathered and analysed. A way to do so is to regress the speed of adoption on every relevant property difference perceived by adopters. Had A and B exactly the same properties but design, one could still argue that B was more fashionable, existed in a wider variety of colours, or was more ergonomic, to explain why it got ahead. Any combination of property differences could also be investigated as a cause for early adoption; this means considering potential interaction effects between the independent variables of the regression model. As a matter of fact, a lot of alternative hypotheses can be formulated to account for B's early advantage. Nevertheless, the quantity of information required to test them is likely to exceed by far the quantity of information available in existing historical accounts about the case under scrutiny. The VHS controversy provides a good illustration of the argument. Arthur (1990, p. 92) describes the similarity of VHS and Betamax along three properties: price, time of market entry, and initial market shares. He infers that the final victory of VHS can only be explained by a contingent lead amplified by increasing returns. Liebowitz and Margolis (1995, p. 222) contest Arthur's example by considering a fourth property that could account for the domination of VHS, namely its longer recording time – a property particularly valued by consumers in the late 1970s.

Many non-contingent properties can explain the outcome of adoption patterns, yet it is practically impossible to isolate structural causes when we observe a unique historical trajectory. Therefore, the contingency assumption of path dependence is falsifiable only discursively in historical case studies: while it is feasible to imagine how things could have unfolded differently, it remains impossible to explain scientifically why they happened the way they did. Hence, to rely on contingency is to take the risk of constructing a theoretical edifice on disputable, shaky foundations.

Issue 3: Long Run Suboptimality

Another issue that severely constrains the empirical validity of path-dependent explanation is the idea that history matters 'in the long run'. In the long run, VHS will be replaced by another recording system (e.g. DVD) and QWERTY keyboards substituted for something else (e.g. voice recognition systems). In the absence of exogenous shock, the long run signals the moment when lock-in can empirically be observed. Therefore, the lock-in phenomenon and its timing can be known only *ex post*. Since path dependence predicts lock-in but does not tell when it will occur, the proposition that path dependence implies lock-in suffers from a lack of falsifiability. A simple way to falsify path dependence would be to observe that lock-in has not occurred; but since it cannot be known when it is supposed to occur, one can only acknowledge that lock-in has not occurred *yet*. Thus, the path dependence explanation cannot be falsified because it does not specify a time limit after which the predicted observation (i.e. lock-in) can be said not to have occurred.

Therefore, empirical evidence based on *ex post* case study observations is bound to remain inconclusive (Liebowitz and Margolis, 1995) because it appeals to the observer's subjective perception of what is the long run equilibrium. It follows that one can easily reframe historical narratives in a path-*in*dependent manner by postponing the moment

termed 'the long run': for instance, one could maintain that history did not matter in the VHS vs. Betamax competition since nowadays everyone is locked in using DVDs. To falsify this claim, one needs to prove that a standard inferior to DVD would dominate today's industry had Betamax cornered the market in the 1990s. As we will discuss below, such proof is challenging to provide. Another implication of adopting a subjective viewpoint is that optimality becomes relative to a particular audience. Strategically, it is often optimal for a firm to impose its own technological standard, independent of the inherent welfare implications of the standard at a societal level. What is strategically optimal for a firm is not necessarily optimal for the whole society.

The difficulty of applying the theory of path dependence to historical observations partly comes from the fact that, while some mathematical processes do converge to an uncontroversially stable equilibrium, real history does not. Claims that our world is suboptimal are not unlike Leibniz's attempt, more than three centuries ago, to establish logically that we live in the best of all possible worlds (Leibniz, 1686/2000). Path dependence scholars, with their emphasis on suboptimality, maintain that we do *not* live in such an optimal world (David, 1985), because had the past been different, we could all be better off right now (e.g. nobody would use inferior QWERTY keyboards). The theorem of path dependence asserts that the past shapes the present stochastically: $\forall(O, I), Pr(O \mid I) < 1$. Thus, at the present time, no one can determine what today would look like had the past been different, since the dice of contingency would need to be rolled again from that point in the past onwards.

Assuming path dependence theory holds logically, let us analyse suboptimality claims with the language of propositional logic. The context is the same as above: two independent firms propose technologies A and B which compete for adoption; *ex post*, B corners the market but is found suboptimal. In the following, C_B means that 'contingent events put B's adoptions ahead of A's', SR means that 'self-reinforcement occurs and alternative paths are selected out', L_B means that 'the process is eventually locked-in on B', and I represent 'initial conditions'. Say A and B are technologies, then initial conditions represent strategic decision variables such as price, design, or technical specifications. When path dependence results in suboptimality:

(1) $\forall I, C_B \wedge SR \rightarrow L_B$ — *For any set of initial conditions, if contingent events puts **B** far enough ahead of **A**, and the path is later reinforced, then the process is locked-in on **B**.*

To understand how suboptimal lock-in on B could have been avoided, let us analyse the contrapositive of Proposition (1):

(2) $\forall I, \neg L_B \rightarrow \neg C_B \vee \neg SR$ — *By contraposition, for any set of initial conditions, if the process is not locked-in on **B**, then **either** contingent events did not put **B** far enough ahead, **or** self-reinforcement did not occur on path B (e.g., it was stronger for **A**).*

An important aspect of path dependence becomes salient in Proposition (2). From a path dependence perspective, it is not possible to identify precisely *ex post* why a particular

outcome did not occur, for contingency or self-reinforcement – or both – can be involved in the non-selection of a given path. *Ex post*, we are not in a position to identify: (i) what should have been different in the past to have a different future; and (ii) whether human agency could have made that critical course of events different or not.

To illustrate this idea, let us imagine a counterfactual world wherein Betamax won over VHS. In our actual world, the cash generated by VHS's success was reinvested to further improve image quality, and led to the design of the superior S-VHS standard. But in the counterfactual world, Sony's cashflows were entirely redistributed to shareholders, and the Betamax standard never improved enough so as to match the S-VHS technology. Worse, consumers got used to the idea that Betamax had reached the highest video quality possible, and no firm ever saw the market opportunity to develop a better standard, such as DVD.

This thought experiment helps us to understand the vacuity of hypothetical regret (i.e. 'if only the past had been different, then . . .') in a path-dependent world. When one maintains that QWERTY is suboptimal and that Betamax would have led to a better future, one implicitly contradicts a core theorem of path dependence, i.e. $\forall(O, I), Pr(O|I) < 1$. That is, one mistakenly assumes contingency would have influenced an alternative path (Betamax) in exactly the same way it did for the actual path taken (QWERTY), an assumption contradicted in Proposition (2): the fact that something does not happen cannot tell us anything about the influence of contingency on its non-occurrence. As we have argued, not only is such a statement contradictory to path dependence theory, but it is also impossible to falsify. Hypothetical regret, as a corollary of the claim that the world is suboptimal, precludes path dependence theory from being empirically tested. The proposition that 'the current world is suboptimal' is at best misleading; the strongest claim one can make is that we could have been better off today with a probability strictly comprised between zero and one. Ironically, it follows that we cannot turn down with certainty the proposition that we are currently living in the best of all possible worlds (see Appendix 2.2). After all, Leibniz was perhaps not that far from the right path.

THE FUTURE OF PATH DEPENDENCE: RESEARCH IMPLICATIONS

Beyond the theoretical challenges raised in the first section of this article, *ex post* empirical studies of path dependence raise serious epistemological concerns. Properties ignored in historical accounts (e.g. VHS's longer recording time) can be brought into the picture to disconfirm explanations based on path dependence. The latter rely on the assumption that contingent events matter in the long run, yet contingency cannot be verified and 'the long run' is often defined *ad hoc* to fit conveniently the observed phenomena. Based on the previous sections, we argue that the theoretical substance of path dependence would more readily apply to situations where: (i) the complexity of the observed system can be circumscribed to a small and finite amount of properties; (ii) the contingency hypothesis is not used as a patch for lacking data but is a credible assumption; and (iii) the long run equilibrium is not defined *ex post*.

Three broad categories of research designs meet these requirements: computer-based simulations, experimental studies, and counterfactual investigation. First, computer

simulations present obvious advantages that enable researchers to define initial conditions, model contingency, and determine self-reinforcing mechanisms. 'A computer simulation can take a complex set of assumptions, simulate a set of organizational processes, and represent the implications of these processes for organizational outcomes' (Lant and Mezias, 1990, p. 151). Simulations force researchers to make explicit assumptions about a finite amount of known variables that can be controlled for. Researchers are thus able to 'generate multiple historical trajectories emanating from the same set of initial conditions, thus enabling them to generalize about the mechanisms and processes that produce such histories (a case study, in contrast, must rely on the observation of one historical path)' (Zott, 2003, p. 109). Simulations can help assess the probability of path dependence given a set of initial conditions, a certain amount of contingency, and the nature of self-reinforcement, thereby providing scholars with estimates of the probable frequency of path dependence in organizational life. For instance, Zott (2003) questions the conventional wisdom on path dependence and dynamic capabilities and demonstrates in a simulation study that path dependence is not a necessary property of capability development. Simulations have the potential to record the detailed characteristics of unfolding processes. They can be re-run and their results compared since complete data series are available for each relevant variable. It then becomes possible, unlike in *ex post* historical accounts, to trace the complex mechanisms that led (or not) to lock-in.

Moreover, simulations display high internal validity and are particularly well suited to study longitudinal process phenomena (Carley, 2001; Davis et al., 2007). When looking at complex phenomena over time, simulations help answer the question 'What if?' rather than 'What happened?' (Dooley, 2002), which makes them especially interesting for disentangling the intricacies of contingency. In this vein, Sterman and Wittenberg (1999) simulate the path-dependent emergence of scientific paradigms and observe that it is largely driven by situational characteristics of the environment. For instance, they find that the confidence level that other paths represent serious alternatives decreases the probability of lock-in. In their simulation of path-dependent organizational search processes, Becker et al. (2008) observe that organizational exploration and coordination mitigate the potentially harmful effects of path dependence. Akkermans and Romme (2008) simulate the path-dependent evolution of a supplier network and find that initial conditions – inner dispositions towards network partnership – have little predictive value for the actual behaviour of network agents (for another simulation of search paths controlling for the inner dispositions of search agents, see Winter et al., 2007). In their simulation consistent with the theorem of path dependence (i.e. $\forall(O, I), \Pr(O \mid I) < 1$), contingent life events trigger path dependence, which is later reinforced through enactment and sensemaking processes to determine outcome network behaviour. All in all, the interest of simulation for future research on path dependence resides in its ability to identify the contextual criteria that increase or decrease the likelihood of lock-in, or mitigate its effects on technological, strategic, and institutional phenomena.

Second, lab experiments broadly exhibit the same properties as simulations when it comes to testing path dependence at a defined level of analysis: individuals and small groups (Webster and Sell, 2007). Experiments also deal with the controlled manipulation

of a finite amount of variables, which renders falsification procedures feasible. Like in simulations, choices are not assumed *ex post* to be contingent, but are actually modelled as the consequence of a random sampling procedure. While in a simulation the impact of chance can be estimated by re-running the simulation with a different random seed, in a lab context the experiment can be replicated with different, randomly-chosen subjects. Using such designs, scholars can tell what is attributable to chance and what is not, since all relevant variables are tracked at each step of the research process. In a controlled experimental study of decision processes, Koch et al. (2008) find that 'path dependency results from poor decisions that are due to the fact that people in highly complex situations tend to neglect future developments at the expense of information on present situations'. Arguably, this finding can only appear when different experimentally-controlled paths are compared along the dimension of decision complexity. Importantly, since simulation and experimental parameters are set *ex ante* by the researcher, the time boundaries of these studies are not subject to *ad hoc* determination based on *ex post* observations. Parameters can be subsequently modified in replication studies to actually compare various regions of equilibria, which provides sufficient support for claims about suboptimal paths. Experimental design can be used to study controlled property differences. For example, Bach (2008) accounts for which property differences between cable and DSL explain adoption in the German broadband market. Looking at speed, price, contract duration, and technology, findings show that to compensate for an initial lead in DSL adoption, cable operators need to propose contracts whose perceived utility is at least 18 per cent higher than that of comparable DSL packages. In sum, simulation and experiments address all three epistemological issues discussed earlier in the paper and thus make non-metaphorical path dependence more readily testable and falsifiable.

Third, counterfactual investigation of causal relationships offers promising methods to study causal relationships (Durand and Vaara, 2009). Counterfactuals are conditional statements that test logically (thought experiments) or probabilistically (computer-aided modelling) the direction and stability of a relationship between two or more events. Using primary and secondary data to construct event sequences, counterfactual history provides methods to ponder whether 'what-if' questions modify the associative structure of recorded facts (Tetlock and Belkin, 1996; Tetlock and Parker, 2006). Conceptual clarity, cotenability, consistency, and projectability are pivotal principles that could help classical case studies to move away from the suboptimal path on which they currently stand. Counterfactual case studies could shed light on the contingency conditions that brought about a triggering event and on the prevailing reinforcing mechanisms which both combined resulted in path dependence. Causal modelling (Pearl, 2000; Spirtes, Glymour, and Schines, 2000) offers more systematic exploration of causal relationships. Causal modelling tests the direct and conditional associations between events, assesses the presence of unobservable factors in a dataset, and proposes techniques to block *ad infinitum* regression (e.g. conditioning, instrumenting, and mediating techniques). This systematic exploration of data associations could prove useful in exhausting the condition sets that prevail in defined path-dependence situations. This would avoid the *ad hoc* specification of A or B's characteristics – which are unverifiable or unfalsifiable – or the sterile debates about suboptimality.

CONCLUSION

Our redefinition of path dependence helps investigate the conditions under which the concept can advance our knowledge of organizations. Path dependence, which is not about hypersensitivity to initial conditions, can exist without increasing returns. Path dependence predicts lock-in only when contingent events amplified by a self-reinforcement mechanism causes alternative paths to be selected out. Contingency and various components of self-reinforcement are widespread in organizational life, so path dependence must be at play out there, even though its most visible consequences may be found in exceptional and long-lasting cases of extreme performance levels. So far, most attempts to apply path dependence empirically have not satisfactorily addressed important epistemological issues, such as how to verify or falsify contingency, how to define 'the long run', and how to speak adequately of suboptimality given the core theorem of path dependence, i.e. $\forall(O, I), P(O \mid I) < 1$.

This paper has explicitly opted in favour of narrowing the definition of path dependence, thereby enabling scholars to specify what conditions need to be met to characterize a historical sequence as path-dependent, and to distinguish a path-dependent process from its outcome. In turn, we suggest more adequate methodologies to tackle the so far overlooked issue of empirical testability. We believe a cautious and rigorous use of path dependence has a strong potential for organization scholars interested in institutions, technology and dynamic capabilities, provided that the concept is well defined, clearly identifiable and distinct from sister notions, and appropriately measured. However, we also recommend that path dependence be used parsimoniously, especially since to date, consensual empirical evidence of path dependence is scarce. When other theoretical notions (e.g. first mover advantage, imprinting, or inertia) and their related assumptions display a better fit with the data, there is no need to invoke path dependence (Table I).

Thus, when path dependence is used in empirical research, we recommend that scholars: (i) stipulate what relevant properties of institutions, technologies, or capabilities should be taken into account to compare alternative paths (in the case of VHS vs. Beta: price, time of entry, image quality, recording time); (ii) make clear what are the potentially crucial contingencies that occurred and when they occurred; and (iii) specify for each path what components of self-reinforcement are at play and for how long. Following these steps helps flesh out more robust hypotheses regarding the possible presence of path dependence. Moreover, the development of controlled research designs like simulations, experiments, and causal modelling is the only way to potentially supply strong evidence of this specific form of history dependence.

Our position in this paper is that exogenous shocks are required to shake the system free of its history. This view has the merit of consistency since it preserves the explanatory power of structures over time: for instance, we do not need to posit, for obscure reasons, that institutions suddenly cease to produce constraining institutional effects on the moment the system escapes lock-in (Schneiberg, 2007). However, this conception of path dependence should be qualified as it displays some limitations. First, path self-reinforcement is not endless. Economies of scale, for example, cannot yield additional profit indefinitely. As noted by Ruttan (2001), paths can sometimes exhaust themselves endogenously. Second, paths can unfold simultaneously in several environments. Institu-

tions relate to multiple environments, firms operate in diverse industries, and dynamic capabilities can serve different business units across markets submitted to various selection criteria. Bassanini and Dosi (2001) show that path coevolution implies fitness maximization across different landscapes, and as becomes visible in NK models with multiple local peaks, misfit in one landscape can cause a major discontinuity along the whole path, as if local lock-out created global path breaking. Therefore, there may exist endogenous conditions for exiting the lock-in situation that will require further investigation.

Hirsch and Gillespie (2001, p. 87) ask whether 'path dependence contain[s] any value added over existing theories of innovation and social changes' – our answer is YES. However, path dependence is not a theoretical Russian doll hosting every possible story of the 'history-matters' type. There is potential for a non-metaphorical conceptualization of path dependence to inform organizational research, just like many other theories do. This paper has sketched the contours of a testable theory of organizational path dependence, and indicated how future research could be designed. Hopefully this will help sociologists, economists, and organization and management scholars pursue the path dependence research agenda on a sounder basis.

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NOTES

[1] Terms marked with * on their first occurrence are defined in the glossary (see Appendix 3).

[2] Path dependence implies that how paths are created and how they are sustained are different mechanisms (Stinchcombe, 1968, pp. 104–16). Without contingency, alternative paths would be known *ex ante* and there would be no unpredictable outcome. So without contingency, the same structural cause would explain why a path was both chosen in the first place and subsequently pursued – most probably because it first seemed the best of all. Thus, path dependence is distinct from structural explanations to the extent that path creation and path reinforcement are two necessary building blocks that correspond to different underlying mechanisms (Schwartz, 2004).

[3] Path dependence should clearly be distinguished from hypersensitivity to initial conditions, a notion central to chaos theory. Path dependence deals with stochastic processes, whereas chaos theory is concerned with deterministic yet unpredictable systems (see Table I).

[4] These examples illustrate the kind of phenomena that should attract the attention of path dependence scholars. We do not imply that they constitute indisputable evidence of path dependence, for reasons developed in the next section.

[5] In the sense described earlier in the paper. Reference to luck or chance as a source of competitive advantage (Barney, 1986) has triggered a comparable controversy in the field of strategic management (Priem and Butler, 2001). For theories to have empirical content, law-like necessity must characterize the association of two phenomena. Since luck cannot *imply* sustained competitive advantage, the RBV cannot uncontroversially rely on luck to predict firm success.

[6] This is a simple application of Leibniz's law of the identity of indiscernibles (Hacking, 1975; Leibniz, 1686/2000), which states that no two distinct entities have got exactly the same properties (Forrest, 2006; see Appendix 2.1). See Durand (2002) for a discussion of identity assumptions as a common basis for industrial organization and RBV arguments.

APPENDIX 1: NON-ERGODIC MARKOV CHAINS

Path dependence is a property of non-ergodic Markov chains that have at least two possible equilibria selected contingently along the path. A stochastic process consisting of a sequence of random variables $\{X_n, n = 0,1,2, \ldots\}$ with a finite or countable number of possible values and that has, for any state i, a fixed probability P_{ij} that it will next be in j is called a *Markov chain* (e.g. Ross, 1996). Any Markov chain verifies the Markov property stating that the future only depends on the present:

$$\Pr(X_{n+1} = x | X_n = x_n, \ldots, X_1 = x_1) = \Pr(X_{n+1} = x | X_n = x_n).$$

- A Markov chain is *irreducible* if all states communicate with each other.
- State i has *period* d if $P_{ii}^{\ n} = 0$ whenever n is divisible by d and d is the greatest integer with this property. A state is said to be *aperiodic* when it has a period of 1.
- State i is *recurrent* if with certainty a process starting at j will eventually return; it is *positive recurrent* if the expected number of transitions needed to return is non-null and finite.
- An irreducible aperiodic Markov chain with only positive recurrent states is said to be *ergodic* (Ross, 1996, ch. 4). It has a stationary distribution, i.e. one that verifies, for all n:

$$\Pr(X_{n+1} = x | X_n = y) = \Pr(X_n = x | X_{n-1} = y).$$

When a Markov chain is ergodic, it is possible to reach a given state from any other state through a certain sequence of events. As a consequence, a Markov chain is *non-ergodic* if it is either non-irreducible, non-aperiodic, or non-positive recurrent.

APPENDIX 2: FORMAL DEVELOPMENTS ABOUT SUBOPTIMALITY

1. Identity of the Indiscernibles

Using the notation of predicate logic, A and B representing alternative options and P any property characterizing them, the argument about the existence of distinctive properties can be written:

$\forall P[PA \leftrightarrow PB] \rightarrow A=B$	*(if for any property P, A and B have P, then A*
$A \neq B$	*and B are identical; A and B are distinct;*
$\therefore \exists P[(PA \wedge \neg PB) \vee (\neg PA \wedge PB)]$	*therefore, there is at least one property P along which A and B differ.)*

2. Suboptimality

The claim: 'we might be living in the best of all possible worlds' does not contradict the theorem:

- The current outcome O belongs to the set of all possible outcomes S. Assume O is the optimal outcome (whatever the criteria for optimality). Thus $O \in S$, $x \in S$, $O > x$.
- Let us posit the existence of Q, a better outcome than O ($O < Q$). Yet, we cannot prove that $Q \in S$, since there is no deterministic relationship between the past states and the possible outcomes. Therefore, the probability that we live in the best of all possible worlds is non-zero.

APPENDIX 3: GLOSSARY OF TERMS MARKED WITH*

Contingency: Consistent with prior path dependence research, contingent refers to unpredictable, non-purposive, and seemingly random events

Ergodicity: Property of a dynamic system wherein it is possible to reach a given state from any other state through a certain sequence of events (more details in Appendix 1)

Falsifiability: A scientific proposition is falsifiable if it can be refuted empirically

Increasing (decreasing) returns: Under increasing (decreasing) returns, a choice made at time t becomes more (less) likely to be made again by the same agent at time $t+1$. Economies of scale are a particular instance of increasing returns: a firm producing more decreases its unit cost and is therefore enticed to further increase production in the future.

Leibniz: Leibniz (1646–1716) is a German philosopher, logician, and mathematician.

Lock-in: A situation of relatively stable equilibrium, caused by path dependence, from which it is difficult to escape without the intervention of shocks exogenous to the system.

Necessary condition: A necessary condition of a proposition is one that must be satisfied for the proposition to be true.

Positive (negative) externalities: Under positive (negative) externalities, a choice c made at time t by an agent increases (decreases) the utility derived by another agent from choice c' made at time $t+1$. Externalities differ from returns in the sense that they modify the utility function of agents not directly involved in the initial decision (e.g. users of a different product, future users, stakeholders).

Property: Anything that can be said to characterize an entity. Properties include the attributes or qualities or features or characteristics of things. Properties have causal powers.

Self-reinforcement: A set of mechanisms endogenous to a given path that makes it more and more dominant over time relative to alternative paths.

Stochastic: A stochastic system includes a predictable and a random component. It is non-deterministic.

Suboptimality: A situation is suboptimal if there exists a tenable alternative situation which would increase agents' utility relative to the suboptimal case.

Testability: A theory is testable when there exist methodological instruments that allow for the investigation of the empirical propositions one derives from it.

Verifiability: A proposition is verifiable if there exist some observable events pertinent for determining its truth or falsity.

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