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Explaining sociotechnical transitions: A critical realist perspective

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ABSTRACT

This paper identifies and evaluates the explicit and implicit philosophical assumptions underlying the so-called multilevel perspective on sociotechnical transitions (MLP). These include assumptions about the nature of reality (ontology), the status of claims about that reality (epistemology) and the appropriate choice of research methods The paper assesses the consistency of these assumptions with the philosophical tradition of critical realism and uses this tradition to highlight a number of potential weaknesses of the MLP. These include: the problematic conception of social structure and the misleading priority given to intangible rules; the tendency to use theory as a heuristic device rather than causal explanation; the ambition to develop an extremely versatile framework rather than testing competing explanations; the relative neglect of the necessity or contingency of particular causal mechanisms; and the reliance upon single, historical case studies with insufficient use of comparative methods. However, the paper also concludes that the flexibility of the MLP allows room for reconciliation, and provides some suggestions on how that could be achieved – including proposing an alternative, critical realist interpretation of sociotechnical systems.

1. Introduction

Research in innovation studies is increasingly focused on the challenge of sustainability – and in particular, the threat posed by climate change. Given the scale of this challenge, it is clear that an effective response will require more than developing and adopting cleaner technologies. Instead, major changes will be required in multiple aspects of the energy, transport, food and other systems that form the basis of industrialised societies. Innovation research has therefore focused increasingly upon how these systems function and how they may undergo far-reaching change (Van den Bergh et al., 2011). The growing literature on these so-called 'sociotechnical transitions' has a range of antecedents and takes a variety of forms, but has increasingly coalesced around a particular theoretical framework: the so-called *multilevel perspective on sociotechnical transitions* (MLP) (Geels, 2002a).

The MLP seeks to explain highly complex, non-linear processes that unfold over many decades, involve multiple social groups and technical artefacts; have unclear boundaries in space and time and lead to uncertain and contingent outcomes. It seeks to track changes in complex systems along several dimensions; and to explain those changes as the result of the alignment and mutual reinforcement of a variety of processes operating at a number of levels. To identify those processes, the MLP draws upon a large and growing range of social scientific theories, several of which employ different and potentially incompatible foundational assumptions (e.g. evolutionary economics and the social construction of technology). This theoretical development informs and is informed by a series of qualitative, historical case studies that typically focus upon single rather than comparative cases and rely primarily upon secondary data (e.g. Geels, 2002a, 2006a).

Since its inception in the early 2000s, the MLP has proved enormously successful, attracting interest from researchers from a wide range of disciplines and stimulating a wealth of theoretical developments and empirical applications.[1] The policy implications of this work have proved more difficult to identify and to communicate, but initial success in the Netherlands (Loorbach and Rotmans, 2010) has been followed by broader interest, including from the OECD (OECD, 2015; EEA, 2016).

Given this range of activity, it is increasingly difficult to keep track of developments and to assess the contribution that the MLP has made. In this context, this paper seeks to take a step back. Instead of applying the MLP to new empirical topics or 'enriching' it with new theoretical ideas, the paper seeks to identify and evaluate the philosophical assumptions that underpin the MLP. These include the explicit or implicit assumptions about the nature of reality (ontology) and the status of knowledge claims about that reality (epistemology), together with the corresponding recommendations for research methodology. These assumptions are insufficiently discussed by practitioners or users of MLP-based research, and deserve more consideration.

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[1] Indicators of this interest include the establishment of an academic journal (*Environmental Innovation and Societal Transitions*) and research network (*Sustainability Transitions Research Network*) that prominently feature MLP-based research.

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To achieve this, the paper introduces a particular philosophy of science, known as critical realism (Bhaskar, 1975, 2014). Although widely used within the social sciences, critical realism has had little influence upon innovation studies. In crude terms, critical realism seeks to bridge some long-standing divisions within the social sciences − such as between positivism and interpretivism. More technically, critical realism combines an 'ontological realism' (the claim that phenomena exist independently of our knowledge of them) with 'epistemological relativism' (the claim that human knowledge is socially produced, historically transient and fallible) and 'judgemental rationalism' (the claim that there are rational grounds for preferring some theories and explanations over others). (Bhaskar, 1975). From a critical realist perspective, the primary objective of social scientific research is not to predict or to interpret but to *explain* − in other words, to develop empirically supported theories and hypotheses about how, why and under what conditions particular phenomena occur. Good explanations will include reference to: the (real) physical and social entities that are considered to be relevant; the relationships between the constituent parts of those entities; the causal powers that result from those relationships; and the contingent combinations of entities and powers that are responsible for particular events (Elder-Vass, 2010). Humean models of causation that rely solely upon correlations between observed events do not meet these explanatory criteria (Lawson, 1997). Neither do they the 'as if'[2]; models proposed by some economists or the 'heuristic devices'[3]; proposed by some sociologists (Lawson, 1997).

The paper argues that critical realism can help to clarify some of the strengths and weaknesses of the MLP, including the validity of claims about the nature and properties of sociotechnical systems, the appropriate criteria for justifying those claims and the relative usefulness of different research methods. Since the MLP is not a homogeneous body of thought, the paper focuses primarily on the work of the leading author in the field − Frank Geels − who has gone further than most in discussing the philosophical foundations of the MLP (e.g. Geels, 2010, 2009). However, the paper is also informed by the broader MLP literature, including studies that have been more critical of its core assumptions (Genus and Coles, 2008; Markard and Truffer, 2008; Shove and Walker, 2007).

The paper organises the evaluation of the MLP around six issues, namely:

1. the distinction between sociotechnical systems and sociotechnical regimes;
2. the conception of social structure and the priority given to 'rules';
3. the definition and boundaries of sociotechnical systems and regimes;
4. the status of the MLP as a 'heuristic device';
5. the necessity or contingency of particular causal mechanisms; and
6. the validity of narrative explanation.

The first three of these are ontological while the remainder are epistemological and/or methodological. In each case, the paper highlights inconsistencies between the nature and application of the MLP and the philosophy of critical realism and uses this to highlight some limitations of the MLP. But the paper also suggests that the flexibility of the MLP allows room for reconciliation, and provides some suggestions on how that could be achieved.

At the time of submitting this paper, there had been no previous evaluation of the MLP from the perspective of critical realism. But during the review process, Svensson and Nikoleris (2018) published a critical realist critique of the ontological foundations of the MLP, focusing in particular on the conception of social structure. As such, Svensson and Nikoleris primarily address point 2 above, although they also make a number of comments on methodology. Their insightful critique is entirely consistent with the arguments that follow, so the two papers should be regarded as complementary. A number of references to Svensson and Nikoleris have therefore been included in what follows.

The remainder of the paper is structured as follows. Section 2 provides an overview of the MLP, illustrating its basic insights and claims with the help of a practical example and summarising its three core analytical concepts − niche, regime and landscape. Section 3 provides an introduction to critical realism, highlighting key ideas such as the concept of emergence. Section 4 identifies the implicit ontology of the MLP and indicates a number of important difficulties, including: the lack of clarity in defining sociotechnical systems and sociotechnical regimes; the problematic attribution of causal priority to the regime; and the reliance upon a theory of social structure (structuration) that effectively conflates structure and agency and downplays the importance of social relations. Section 5 does the same for epistemology and methodology, and highlights the tensions between the use of MLP as a heuristic device and as a causal explanation, the lack of attention to the necessity or contingency of different causal mechanisms and the limitations of 'narrative explanation' and 'process theory' as a model for MLP-based research. Section 6 summarises the key findings and briefly suggests how future research could address some of these limitations.

2. Sociotechnical systems and transitions

The MLP begins with the observation that 'societal functions', such as personal transport, electronic communication, water supply and housing are provided by a cluster of interlinked social and technical entities[4] that are collectively termed a *sociotechnical system* (Geels, 2002a). Relevant entities include technologies, firms, supply chains, infrastructures, markets and regulations. Sociotechnical systems develop over many decades and the alignment and co-evolution of the different entities and practices leads to mutual dependence and resistance to change (Geels, 2002a, 2012; Geels et al., 2012). However, the primary source of stability in these systems is claimed to be the shared rules, norms, expectations and beliefs that guide the behaviour of the different actors within the system − termed the *sociotechnical regime*. *Sociotechnical transitions* are defined as major transformations in these regimes/systems. These typically involve major changes in the technologies that form the core of the system, but they also − and necessarily − involve interlinked changes in many other parts of the system, together with far-reaching changes in the underlying rules and norms (the regime).

To make these ideas more concrete, take the example of the car-based transport system providing the societal function of personal mobility (Geels et al., 2012; Sorrell, 2015). This system is centred on an individual artefact − the car- but this artefact is linked to and dependent upon multiple social and technical entities at a variety of levels. These include, but are not confined to: the global car industry and its many associated supply chains; the car maintenance and distribution network; the global oil industry and the associated infrastructure of oil wells, refineries, pipelines and fuel stations; the road infrastructure and associated industries; the patterns of land use that have developed around that infrastructure, including amenities and workplaces that are only accessible by car; the multiple institutions, regulations and policies associated with the production and use of cars; the engineering skills and knowledge built up over decades in a variety of domains; the

[2] Exemplified by the following statement by Milton Friedman "… Consider the problem of predicting the shots made by an expert billiard player. It seems not at all unreasonable that excellent predictions would be yielded by the hypothesis that the billiard player made his shots as if he knew the complicated mathematical formulas that would give the optimum directions of travel, could estimate accurately by eye the angles, etc., describing the location of the balls, could make lightning calculations from the formulas, and could then make the balls travel in the direction indicated by the formulas.…" (Friedman, 1953)

[3] "… This signifies a concept or idea that is used not so much because it is well supported by the evidence but because it helps us think about the problem…"(Bruce and Yearley, 2006)

[4] The generic term 'entity' is not commonly used within the MLP literature, but is used here to facilitate comparison with critical realism.

technical associations, interest groups and other organisations that are active in these domains; the daily travel routines, behaviour and expectations of millions of car owners; and the symbolism and cultural norms that have become associated with car-based mobility ('car culture') (Unruh, 2000). These different entities and practices coevolve and act together to shape the level and pattern of personal mobility, as well as the environmental impacts of that mobility (Sorrell, 2015).

While individual entities within the car-based transport system are constantly undergoing incremental change, a transition to a more sustainable transport system is likely to require multiple entities and practices to undergo more radical change − such as the substitution of internal combustion engines by battery-electric motors, the replacement of petroleum infrastructures with electrical charging infrastructures, the development of industries and supply chains for batteries and other technologies (along with the decline of existing industries and supply chains), the integration of the transport system with smart electrical grids that may use electric vehicles for electricity storage, the development of new knowledge and skills within each of these areas and the adjustment of users to vehicles that perform differently, are recharged differently, have a shorter range and may no longer be individually owned (Geels et al., 2012). Hence, an improved understanding of how such radical transitions have occurred in the past could potentially inform efforts to transform existing systems in more sustainable directions (Smith et al., 2005, 2010; Geels and Loorbach, 2010; Schot and Geels, 2008; Markard et al., 2012).

Geels (2002b,c, 2004) and other authors (Unruh, 2000; Kemp, 1994; Hughes, 1987; Kemp et al., 2001) have described how sociotechnical systems evolve and become established, how they encourage incremental change along predictable trajectories and how their stability can obstruct more radical change. Sociotechnical systems frequently rest upon core technologies such as the internal combustion engine whose early evolution involves considerable uncertainty. Historical experience suggests that (contrary to the predictions of orthodox economics) apparently inferior technologies can become dominant when they obtain an early advantage that allows them to benefit from various positive feedback mechanisms − such as scale economies that reduce costs, lower prices and encourage increased demand; learning economies that improve product performance, increase product attractiveness and further reduce costs; and network economies that enhance value through the development of complementary goods and services (Unruh, 2000; Arthur, 1989, 1994; Sterman, 2000). As core technologies diffuse, other factors come in to play to reinforce their dominant position, such as: investments in supporting infrastructure (e.g. roads, pipelines, garages); increased knowledge and capabilities in relevant areas (e.g. motor engineering); the growing economic and political power of relevant groups (e.g. the car industry); the establishment of supportive organisations and institutional frameworks (e.g. professional institutions, labour unions, regulations); and the evolving habits, norms and aspirations of different consumer groups (Unruh, 2000). These interdependent and co-evolving entities combine to form economically significant and geographically extensive systems that becomes increasingly entrenched or *locked-in*, making it difficult for technologies and behaviours that diverge in various ways from the dominant system (e.g. electric or fuel cell vehicles, mass transit) to become established (Arthur, 1989; Cowan, 1990).

The MLP aims to understand: the nature, characteristics and modes of functioning of these sociotechnical systems; the sources of inertia in those systems; the conditions under which those systems change; and, in particular, the processes through which transitions to different sociotechnical systems come about. To do so, the MLP combines ideas from evolutionary economics (e.g., variation and selection, path dependence, lock-in), science and technology studies (e.g. actor-networks, social construction of technology) and various traditions within sociology (e.g. structuration, social practices, social expectations). Informed by a series of historical case studies (e.g. Geels, 2004, 2005a,b, 2006b), the MLP explains radical change as the result of interactions between three levels, namely: the *system* itself which may be encountering internal difficulties (or more specifically the rules and norms that guide the actors in the system, namely the *sociotechnical regime*); the *'niches'* in which radical innovations are being developed; and the exogenous socio-economic *'landscape'* that is imposing pressures upon the system. These are briefly elaborated below:

- *Regime*: As indicated, the incumbent *sociotechnical system* refers to the dominant technologies, infrastructures, industries, supply chains and organisations associated with delivering a particular societal function. The actions of the social groups that create and reproduce these systems are influenced by rules, shared meanings, rules of thumb, routines and social norms. These more intangible elements are collectively termed the *sociotechnical regime* (Geels, 2002b, 2004) − although as discussed in Section 4, there is ambiguity and inconsistency in the use of these terms. The regime is claimed to provide orientation and coordination to the activities of different social groups which, together with the social relationships between these groups, provides the primary source of the stability of sociotechnical systems. Innovation in existing systems is mostly incremental and path dependent, owing to 'lock-in' effects such as sunk investments, economies of scale, vested interests, design standards and entrenched social norms. Taken together, these features make sociotechnical systems stable and resistant to change. However, over time it is possible that *tensions* will build up within a system that are difficult to resolve through incremental change and which begin to threaten its stability. For example, the car-based and oil-based transport system may be threatened by growing congestion and worsening urban air quality.
- *Niche:* At any time there are typically several emerging technologies that differ in important respects from those dominant within the incumbent sociotechnical system (e.g. battery-electric vehicles, hydrogen fuel cells, autonomous vehicles). These 'niche innovations' usually perform poorly compared to the established technologies, are relatively expensive and find it difficult to compete (Schot and Geels, 2008; Geels, 2002b, 2004). In addition, they may lack appropriate infrastructure, encounter resistance from potential users and be obstructed by existing regulations. But such innovations may be able to gain a foothold within particular applications, geographical areas or markets, or with the assistance of targeted policy interventions. As with regimes, niche innovations are created and reproduced by social groups working with shared rules, but in contrast to the dominant regime the relevant social networks are fragile and unstable and the rules are malleable and contested − often with several competing technologies, designs and visions. Niche innovations frequently fail, but in some circumstances can gain enough momentum to stabilise their configurations, improve their performance, reduce their cost, achieve more widespread adoption and trigger changes in other system elements. This requires a growing consensus amongst relevant social groups about the appropriate configuration and market potential of the relevant innovations, together with increased access to financial, political and other resources (Kemp et al., 1998; Hoogma, 2002). Under these conditions, the niche has the potential to 'break through' and to challenge the existing regime.
- *Landscape:* The evolution of sociotechnical systems may be affected in various ways by the broader physical, political and economic environment or *landscape* (Geels, 2002b, 2004). The landscape is largely beyond the control of the actors within the system, but it may influence the system through either gradual changes, such as shifts in cultural preferences, demographics, and macro-political developments, or through short-term shocks such as economic recessions. For example, rising oil prices and growing concerns about climate change are exerting pressure on the car-based transport system.

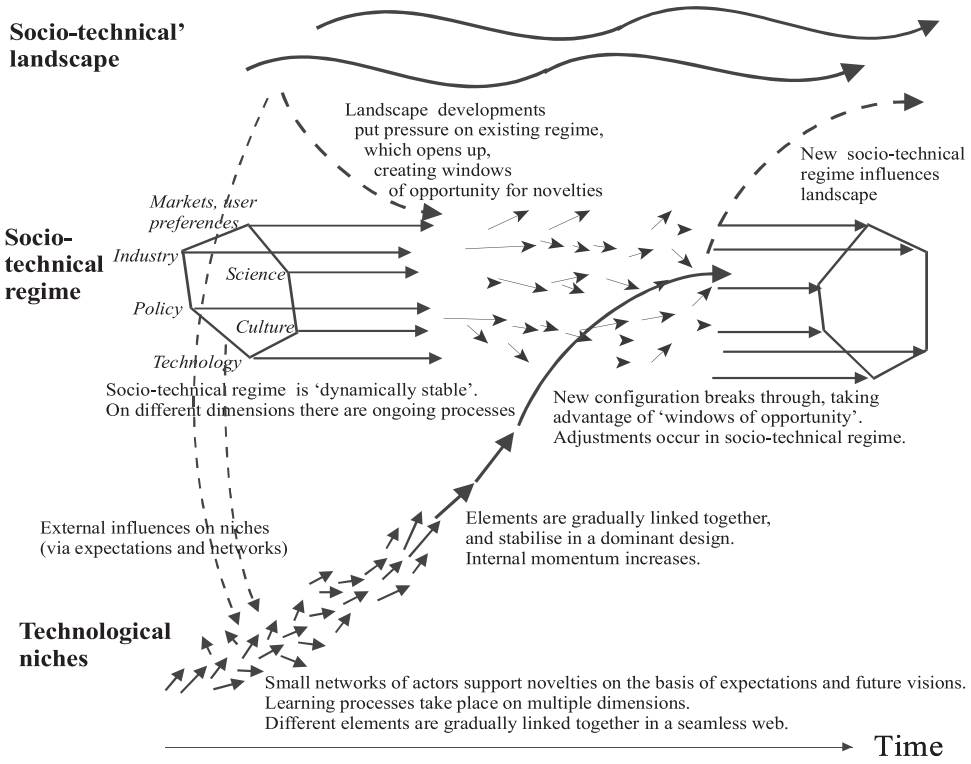

Fig. 1. Multilevel perspective on sociotechnical transitions.
source: (Geels, 2002a).

Case studies of previous sociotechnical transitions[5] suggest that niche innovations can break through when their growing internal *momentum* combines with increasing *tensions* within the existing socio-technical system and growing *pressures* on that system from the external landscape. In combination, these create 'windows of opportunity' for radical change. These changes go beyond the adoption of new technologies and include investment in new infrastructures, the establishment of new markets, the development of new social preferences and the adjustment of user practices and routines. These case studies indicate how, in the context of landscape pressure and internal tensions, successful niche innovations can trigger a series of inter-related technical, economic, social and cultural changes that may eventually combine to create a new and different sociotechnical system based around a different set of core technologies (see Fig. 1).

Since the initial application of this framework by Geels (2004), it has been developed and elaborated in multiple ways. For example, although the narrative of niche-driven transitions remains dominant, the framework has been refined to incorporate a broader range of 'transition pathways' that differ in the nature and timing of the interactions between the three levels (Geels and Schot, 2007). Other authors have highlighted divergences from the standard 'niche breakthrough model', including niche activities being driven by incumbents (Berggren et al., 2015), the importance of technological complementarities (Markard and Hoffmann, 2016) and the co-evolution of different regimes (Papachristos et al., 2013; Raven, 2007). More recently there have been attempts to better integrate power and politics into the MLP (Smith et al., 2005; Kern and Markard, 2016; Meadowcroft, 2009; Avelino and Rotmans, 2009; Geels, 2014) and to better reflect the spatial dimension of transitions (Coenen et al., 2012; Murphy, 2015; Calvert et al., 2017).

The MLP has informed an enormous amount of empirical research,[6] but much of this has focused upon emerging niche innovations and the challenge of steering future transitions in more sustainable directions (Smith et al., 2005; Geels and Loorbach, 2010; Smith et al., 2010; Markard et al., 2012; Verbong and Geels, 2010), rather than explaining the sources and dynamics of historical transitions or critiquing existing accounts of those transitions. Authors using the MLP have also introduced an increasing number of theoretical ideas, partly to compensate for perceived weaknesses with the original framework and to better explain particular transition processes, but also to reflect their particular disciplinary perspectives. The result is a highly complex and ever-growing theoretical framework that is claimed to be applicable to a wide range of systems, contexts and processes (see Section 6). But despite these developments, the underlying ontological and epistemological assumptions of the MLP have received little attention and remain largely unchallenged. Before these can be assessed, it is first necessary to outline the core arguments of critical realism.

3. Critical realism

First developed by Bhaskar in the 1970s (Bhaskar, 1975, 2014), critical realism[7] is an influential philosophy of the natural and social sciences that has informed empirical studies in a variety of areas (Lawson, 1997; Danermark et al., 2001; Easton, 2010; Mingers, 2004; McEvoy and Richards, 2003; Fleetwood, 1999; Fleetwood and Ackroyd, 2004; Blundel, 2007; Downward, 2005; Clark et al., 2007). As a philosophy of science, critical realism cannot be used to assess the validity of particular theoretical claims, but it can be used to evaluate the ontological and epistemological assumptions underlying those claims and

[5] For example: sailing ships to steam ships (Geels, 2002b); propeller to turbojet aircraft (Geels, 2006a), horse-drawn carriages to automobiles (Geels, 2005a), mixed farming to intensive pig husbandry (Geels, 2009); and steam to electric power in factory organisation (Geels, 2006b))

[6] For example, by November 2017, a foundational paper by Geels (Geels, 2002a) had received over 3100 citations on Google Scholar.

[7] This section describes the 'classic' critical realism developed by Bhaskar in his first two books (Bhaskar, 1975; Bhaskar, 2014). Bhaskar subsequently developed 'dialectical' and 'transcendental' critical realism, but these ideas are far less accessible and have correspondingly proved far less influential (Archer et al., 1999).

Table 1
Competing philosophies of social science.
Source: Based on (Mingers, 2006).

	Positivism	Interpretivism	Critical realism
Ontology	Independent and objective reality Causality indicated by constant conjunctions of empirical events	Socially constructed reality Multiple realities possible	Objective, stratified reality consisting of surface-level events and real entities with particular structures and causal properties
Epistemology	Knowledge generated by discovering general laws and relationships that have predictive power Emphasis on prediction	Knowledge generated by interpreting subjective meanings and actions of subjects according to their own frame of reference Emphasis on interpretation	'Retroduction' used to create theories about the entities, structures and causal mechanisms that combine to generate observable events Emphasis on explanation
Methodology	Quantitative methods, such as experiments, surveys and statistical analysis of secondary data	Qualitative methods, such as ethnography and case studies	No preference for a particular method − choice depends upon the research question and the nature of the relevant entities and causal mechanisms. Mixed methods encouraged.

the appropriate methodologies for investigating them. Adherents argue that critical realism offers a more persuasive account of the nature of reality (ontology) and the status of knowledge claims about reality (epistemology) than do competing philosophies of science (Table 1) (Collier, 1994). Owing to lack of space, this claim will not be defended here (readers should refer to Bhaskar's original texts (Bhaskar, 1975; Bhaskar, 2014) and subsequent elaborations by other authors (Elder-Vass, 2010; Collier, 1994; Sayer, 1992; Porpora, 2015). Instead, the subsequent sections will focus on the *consistency* between critical realism and the MLP, and what this says about the strengths and weaknesses of the MLP.

The following summary of critical realism is based upon the accessible introductions by Sayer (1992), Collier (1994), Porpora (2015) and Danermark et al. (2001), and in particular the work of Elder Vass (Elder-Vass, 2010, 2012b, 2012a; Archer and Elder-Vass, 2012). The original motivating question for Bhaskar was: "what must the world be like for science to be possible?" (Bhaskar, 1975). His answer was that there must be an independently existing world of *entities* that have *causal powers and liabilities*, or more generally *causal properties,* as a consequence of the necessary relations between their constituent parts (Bhaskar, 1975; Collier, 1994). When these causal powers and liabilities are triggered they act in combination to create *events*, some of which we observe. The objective of science is to uncover the nature and structure of these entities, to identify and explain their causal properties with reference to their structure, and to use this understanding to explain particular events in terms of contingent combinations of entities and their associated properties. In the case of social events, these entities include human beings with their power of conscious, reflective thinking. Critical realism accepts that scientific knowledge is provisional, fallible and historically relative (i.e. it accepts epistemic relativism), but nevertheless argues that knowledge can progress and that scientific methods can provide grounds for choosing between competing claims (i.e. it rejects judgemental relativism) (Sayer, 1992). Critical realism applies to both the natural and social sciences, although the differences in the nature of the relevant entities leads to corresponding differences in the status of knowledge claims and the appropriate choice of research methods (Bhaskar, 1975; Bhaskar, 2014).

A core distinction within critical realism is between the *real*, the *actual* and the *empirical* (Collier, 1994; Sayer, 1992). The *actual* is those events that occur in the world, while the *empirical* is the subset of events that are actually observed. Lying behind these events is the domain of the *real* which consists of entities of various forms. These entities may be physical (e.g. minerals), biological (animals, people) or social (e.g. families, organisations, markets, language groups) and they may or may not be directly observed − although to support claims of their existence, their *effects* must be observed. Individual entities have particular *causal powers* (the capacity to act in certain ways) and particular *liabilities* (the susceptibility to particular types of change) as a consequence of their internal structure. So for example, water has the power to quench a fire, aircraft have the power to fly, a market has the power to make efficient use of resources and so on.

Individual entities are wholes formed from a set of parts (i.e. other entities) that are related, or *structured,* in a particular way (Elder-Vass, 2010; Sayer, 1992). This structure ensures that the entity persists for a period of time, as well as endowing it with its unique causal properties. So for example, a university is formed from a number of other entities, both material and social (e.g. departments, academics, buildings, equipment, legal frameworks), whose structural relationships endow the university with the power to recruit staff, raise finance, conduct research, teach students and award degrees. In turn, these constituent entities are also internally structured and have their own causal properties.

The relationship between two or more entities may either be *necessary* or *contingent*. For example, there is a *necessary* relationship between a tenant and a landlord, since a person or organisation cannot be a tenant in the absence of a landlord (Sayer, 1992).[8] In contrast, although the personal characteristics of the landlord may affect the tenant in various ways, they are a *contingent* feature of their relationship (Sayer, 1992). Structure may then be defined as the set of *necessary* relationships between the constituent parts of an entity.

When actualised, the causal properties of an entity will *tend* to bring about certain events (Sayer, 1992). For example, when water is thrown upon a fire it will tend to put it out. But *whether* particular causal powers are actualised, and whether or not they bring about particular events, will depend upon a variety of other, contingent conditions − such as the intensity of the fire, the strength of the wind, the flammability of the relevant materials, and so on. Depending upon the circumstances, the same causal power may lead to different events (e.g. the fire may or may not be quenched), and the same event may result from different causal powers (e.g. the fire may be quenched by CO_2 rather than water). The same applies to the social realm, although here the relevant entities are fundamentally different in character (see below). For example, a firm may *tend* to minimise costs as a consequence of its internal structure, the roles assigned to its employees and the incentives provided by the markets in which it operates. But *whether* it minimises costs will depend upon the capacities, ideas, propensities and beliefs of its employees, the information and resources available to them, the market structure and a range of other contingent and contextual factors and influences.

Events in the world are typically the net result of the simultaneous operation of multiple causal mechanisms associated with the contingent combination of multiple entities. Hence, an invariant association between particular causal mechanisms and particular types of event may

[8] The relationship may not be symmetric however: for example, it is possible to be a landlord in the absence of a tenant.

only be expected under rather special conditions − namely when the relevant entities and mechanisms remain stable, together with the conditions under which those mechanisms operate. The experimental method in natural science aims to create such conditions and therefore to isolate the operation and to identify the effects of individual causal mechanisms. But such conditions are difficult to reproduce in the social world: first, because social entities and their associated causal properties are prone to change (e.g. people learn and change their behaviour) and second; because the contextual conditions influencing events are difficult or impossible to control (for). Hence, regular associations between underlying causal mechanisms and particular types of event are likely to be much less common in the social world. We may, however, observe *partial* regularities over more limited periods of time (such as the inverse relationship between the price of a good and the quantity sold within a market) which, when present, can assist in the identification of particular causal mechanisms (Lawson, 1997; Ron, 2002; Porpora, 2001).

These considerations lead critical realists to reject 'positivist' philosophical frameworks that understand causality as a regular succession of empirical events ('if A then B'). Not only are such regularities relatively uncommon (especially within the social world), reliance upon them reduces our understanding of causality to the level of the empirical, rather than the real. Causality should instead be understood as an inherent property of entities, deriving from their internal structure and creating a *tendency* to produce particular outcomes. The identification of empirical regularities (e.g. through a regression model) may provide evidence for the operation of particular causal mechanisms in particular circumstances, but does not *explain* the mechanisms involved. Nor is the identification of such regularities a necessary precondition for causal explanation (although they certainly help) (Easton, 2010). Instead, qualitative research methods such as case studies and ethnography may be more appropriate for uncovering the complex and contingent mix of entities and mechanisms (including people's conscious and unconscious motivations and choices) that together explain particular events in the social world (Danermark et al., 2001; Sayer, 1992). But while the choice of methodology will depend upon the research question, in all cases the primary goal should be *causal explanation*.

A central theme of critical realism is *emergence*. Entities are structured, and those structures are nested within other structures. Some of the causal properties of entities *emerge* from structured relations between their constituent entities, but are not possessed those constituents individually. To take the most commonly cited example, the power of water to quench fire emerges from the causal powers of hydrogen and oxygen, but is not reducible to them. Similarly, the power of a landlord to extract rent from a tenant emerges from the structural relationship between the two, and is not reducible to the characteristics of the individuals involved.

While entities may have some properties that are simple aggregations of the properties of their constituent elements (e.g. the mass of water is reducible to the masses of hydrogen and oxygen), the definition of entities relies upon the existence of emergent causal properties that in turn derive from the properties of the constituent parts and the necessary *relationships* between those parts. Since it not possible to explain the causal properties of entities without reference to these internal relationships, the properties belong to the entity and not solely to the constituent parts (Elder-Vass, 2010). Critical realism is therefore critical of reductionism in general and 'methodological individualism'[9]; in the social sciences in particular. While reductionist explanations may sometimes be appropriate and sufficient, an insistence upon them blinds the researcher to the possibility of emergent causal properties. Critical realism further claims that emergent properties *downwardly influence* entities at a lower level. So for example, in carrying out their job, a lecturer is influenced by the rules and expectations associated with the roles they perform within the higher-level entity of the university.

As can be seen from the above examples, critical realism is equally applicable to the behaviour of natural and social entities, but these also differ in important ways.[10] For example, social entities (such as firms and political parties) tend to have poorly defined spatial boundaries, to change rapidly over time and to be composed of 'parts' (e.g. people, organisations) that are simultaneously members of multiple other social entities (Elder-Vass, 2010). Furthermore, the existence of social entities depends entirely upon the activities of the people that they govern (Bhaskar, 2014) and those people typically have conscious or tacit understandings of the meaning, structure and mode of functioning of the relevant social entity, including the associated relationships, rules and norms (Elder-Vass, 2010; Sayer, 1992; Porpora, 2015; Archer, 1995). However, both natural and social entities may constrain and enable individual behaviour, whether or not they are recognised or understood by those individuals.

This leads to a distinctively critical realist perspective on *social structure*, although different authors provide different interpretations of this term (Elder-Vass, 2010; Porpora, 2015; Archer and Elder-Vass, 2012; Archer, 1995, 2003). A common theme is that social entities have emergent causal properties that derive from the necessary relations between the people and artefacts of which they are comprised, but which are mediated through individual agency (Elder-Vass, 2010). These social relations shape but do not determine the interests, resources, understandings and expectations of the constituent actors; and thereby their actions. The resulting structured interactions give the social entity causal powers − such as the power of a university to award degrees, the power of an orchestra to play a symphony, or the power of a social group to enforce a particular norm (Elder-Vass, 2010, 2016). Social entities therefore enable, constrain and motivate the actions of individuals and are in turn either *reproduced* or *modified* by those actions. So for example, in choosing how to behave at a dinner party, a guest will be influenced by previous and contemporaneous exposure to other individuals who approve or disapprove of particular behaviours, thereby encouraging them to act in ways that *reproduce* the norms of social dining. Similarly, in choosing particular political strategies, a lobbyist will be influenced by the distribution of rights, obligations, interests and resources inherent in the relational structure of a capitalist market economy, but if her strategies are successful she may *modify* the structure of that economy (Porpora, 1989). Both the circle of people committed to enforcing the norms of social dining and the capitalist market economy may be understood as social entities with emergent causal powers − although these differ widely in character and scale (Elder-Vass, 2010, 2012b).[11]

· Having summarised the core elements of both the MLP and critical realism, we can now examine the consistency between the two. This will be achieved in two stages: first, by examining the *ontological* status of sociotechnical systems; and second, by examining the *epistemological* status of knowledge claims about those systems together with the associated research *methodologies*. The analysis identifies a number of important tensions between assumptions made by the MLP and the philosophy of critical realism. With regard to *ontology*, these tensions relate to the ontological status of sociotechnical regimes

[9] Described by Popper (Popper, 2012) as follows: "… All social phenomena, and especially the function of all social institutions, should always be understood as resulting from the decisions, actions, attitudes etc., of human individuals, and that we should never be satisfied by an explanation in terms of so-called 'collectives…".

[10] "…… the *predicates* that appear in the explanation of social phenomena will be different from those that appear in natural scientific explanations and the *procedures* used to establish them within certain vital respects be different to (being contingent upon, and determined by, the properties of the objects under study); but the *principles* that govern their production will remain substantially the same…" (Bhaskar, 2014)

[11] See Elder Vass (Elder-Vass, 2010) for an elaboration of this understanding of social structure

(intersubjective rules) *vis-a-vis* sociotechnical systems (physical artefacts and social relations) and the difficulties of attributing explanatory priority to the former. With regard to *epistemology* and *methodology,* these tensions relate to the use of the MLP as a 'heuristic device' rather than the basis for causal explanation, the lack of attention to the necessity or contingency of different events and causal mechanisms and the insufficient use of research methodologies that could distinguish the necessary from the contingent. These themes are elaborated in the following sections.

4. Sociotechnical ontology

4.1. Systems and regimes

The central constructs of the MLP are the sociotechnical regime and the associated sociotechnical system − since niches and landscapes are defined in relation to those regimes/systems. While systems and regimes are frequently conflated in the empirical literature, the theoretical literature distinguishes between them − although the precise nature of that distinction is not always clear (e.g. Geels, 2011, 2010, 2009, 2004; Geels and Loorbach, 2010; Geels and Schot, 2010). The most common interpretation is that the regime represents the *internal* rules, norms, expectations and beliefs that guide the behaviour of different actors, while the system represents the *external* artefacts and social organisations that work together to deliver a societal function.

> "…*System* refers to tangible and measurable elements (such as artefacts, market shares, infrastructure, regulations, consumption patterns, public opinion), whereas *regimes* refer to intangible and underlying deep structures (such as engineering beliefs, heuristics, rules of thumb, routines, standardised ways of doing things, policy paradigms, visions, promises, social expectations and norms)…." (Geels, 2011)

> "… The sociotechnical regime forms the 'deep structure' that accounts for the stability of an existing sociotechnical system. It refers to the semi-coherent set of rules that orient and coordinate the activities of the social groups that reproduce the various elements of sociotechnical systems… Examples of regime rules are cognitive routines and shared beliefs, capabilities and competencies, lifestyles and user practices, favourable institutional arrangements and regulations, and legally binding contracts…" (Geels, 2011)

The first quote is unsatisfactory from a critical realist perspective since it partly defines sociotechnical systems in terms of *measures* of things (e.g. market shares, public opinion) rather than constituent *entities* (e.g. firms, institutions). The second quote is also unsatisfactory, since it defines the structure of sociotechnical systems as residing in the rules followed by different actors, rather than in the relationships between the entities that comprise the system − which in turn shape those rules (Section 3). Both quotes define sociotechnical regimes in terms of 'intangible' *rules*, but some of these rules (e.g. legally binding contracts, regulations) appear more tangible than others (e.g. cognitive routines) and regulations are defined as part of the system in the first quote and part of the regime in the second. Similar ambiguities can be found throughout the MLP literature.

The focus on rules can be traced back to Nelson and Winter (1982) who highlight how the cognitive routines of engineering communities encourage incremental innovation along particular trajectories ('technological regimes'). Rip and Kemp (1998) and Geels (2000b,c, 2004) widen this concept to include the rules that guide the activities of the other social groups associated with a technology − such as users, policymakers, financiers and suppliers − thereby renaming the concept 'sociotechnical regimes'. Building upon Scott (1995), Geels (2004) helpfully distinguishes between regulative, normative and cognitive rules (Table 2) and shows how these reinforce one another. For example, the laws regarding road use and driver behaviour reinforce the social norms regarding considerate driving. But these rules differ in character: for example, normative rules are primarily intersubjective and enforced through approval or disapproval by other individuals within a 'norm circle' (Elder-Vass, 2010, 2012b; Archer and Elder-Vass, 2012), while regulative rules are primarily embedded in written documents and enforced by the coercive power of the state or other social institutions. Hence, to label all these rules as 'intangible' is problematic.

Further difficulties are created by the lack of consistency in distinguishing between regimes and systems. For example, in Geels (2004), the regime is defined as comprising three interlinked components, namely:

1. physical *artefacts*, such as machines, materials and infrastructures;
2. social *groups*, such as engineers, firms, suppliers, universities, users and policymakers; and
3. intangible *rules*, such as regulations, standards, cognitive routines and social norms.

This definition effectively subsumes the system within the regime. It is not clear, therefore, whether the 'semi-coherent set of rules' *defines* a sociotechnical regime that in turn *structures* a sociotechnical system, or whether the rules form *part* of a sociotechnical regime that also *includes* the sociotechnical system. The first definition is more common in the theoretical literature on the MLP (e.g. Geels, 2010), but some of the empirical literature comes closer to the second definition − which in turn is more consistent with critical realism. But in either case, the rules are said to inform and coordinate the activities of different social groups and to explain the stability of the sociotechnical system (Geels, 2002b, 2004).

Importantly, the theoretical literature on the MLP gives explanatory priority to the regime, rather than the system. The claim appears to be that the rules and norms guiding different actors explain the social and material relations between those actors, rather than the other way round. As Svensson and Nikoleris (2018) observe:

> "… systemic elements and relations are thus deprived of autonomous causal powers − i.e. they are reduced to a dependent variable − and those not internalised and recognised by agents are even deprived of their indirect influence on transitions. According to this conceptualisation, material artefacts and relations of the system are excluded from structure, and exert a conditioning effect only once instantiated (tacitly or cognitively) in human agency and socio-cognitive rules…" (Svensson and Nikoleris, 2018)

From a critical realist perspective, this is deeply problematic. First, rules are better understood as the emergent outcome of higher-level social entities, such as organisations, which downwardly influence the behaviour of participating individuals. For example, the formal and informal rules people follow within an organisation depend upon their roles within that organisation, the relationship of these to other organisational roles and the patterns of authority and incentives that are associated with those roles (Elder-Vass, 2010). As discussed below, this *relational* conception of social structure is fundamentally different from that implied by the MLP. Second, the focus upon intersubjective rules encourages a neglect of the opportunities and constraints imposed by differential access to material resources − over and above any differences in knowledge, skills and normative dispositions (Svensson and Nikoleris, 2018). Third, the claim that rules "…account for the stability and lock-in of sociotechnical systems…" neglects how the *material* features of sociotechnical systems (e.g. long-lived, capital-intensive infrastructure such as roads and pipelines) contribute to the inertia of those systems and constrain the direction and speed of transitions (Unruh, 2000). Indeed, this focus upon rules may undermine the claim of the MLP to be 'sociotechnical' rather than just social:

> "….The regime is still conceptualised as the rules that guide and

Table 2
The different types of rules constituting a sociotechnical regime.
Source: (Geels, 2004).

	Regulative	Normative	Cognitive
Basis of compliance	Expedience	Social obligation	Familiarity
Mechanisms	Coercive (e.g. punishment)	Normative pressure (e.g. social sanctions)	Learning, imitation
Logic	Instrumentality	Appropriateness	Orthodoxy
Basis of legitimacy	Legally sanctioned	Morally governed	Culturally supported
Examples	Formal rules, laws, sanctions, protocols, standards, procedures	Values, norms, role expectations, duty, codes of conduct	Problem agendas, beliefs, bodies of knowledge, models of reality, categories, classifications, search heuristics

orient behaviour. The addition of technology to the social system is simply the addition of another set of rules.… In other words, the MLP brings in a multitude of factors (technological, policy, science, culture), but not as a conjunctive multiplicity of causes in an open system, but as different sets of rules which actors draw upon in action.…." (Svensson and Nikoleris, 2018)

From a critical realist perspective, it would be more plausible to argue that the stability of sociotechnical systems derives from the necessary relations between their constituent physical artefacts, social entities and (tangible and intangible) rules. Indeed, (Geels, 2004) provides such a framework (summarised in Table 3), even though this appears inconsistent with the emphasis given elsewhere to the priority of intangible rules. From a critical realist perspective, there is no need to give the regime (defined as rules) priority and to do so would be to encourage a neglect of how physical artefacts, the distribution of resources and economic and political relations shape those rules. This points to a deeper problem with how the MLP conceptualises social structure, explored next.

4.2. Structure and agency

In the same way that the regime concept can be traced to Nelson and Winter, the idea that rules provide a 'deep structure' or 'grammar' for a sociotechnical system can be traced to Giddens' structuration theory:

"… regime rules are both medium and outcome of action (duality of structure). On the one hand, actors enact, instantiate and draw upon rules in concrete actions in local practices; on the other hand, rules configure actors…" (Giddens, 1984a)

However, structuration theory has been strongly criticised by critical realists (Archer, 1982, 1995, 2003; Porpora, 1989; King, 2010; Jessop, 2005; Layder, 1985) as part of a larger debate within sociology about the relationship between social structure and individual agency. This vast debate cannot be adequately covered here, but is nevertheless critical since competing assumptions about the nature of the relationship between structure and agency can lead to radically different social theories (Porpora, 2015, 1989). Hence, it is important to identify the implicit assumptions about structure and agency within the MLP and the potential consequences of these for the both the character and explanatory power of the theory.

The basic differences between the critical realist and 'structurationist' perspectives are summarised in Table 4. For critical realists, social structure is the necessary relations between the constituent parts of a social entity, providing it with stability over time and endowing it with emergent causal properties (Elder-Vass, 2010):

Table 4
Contrasting perspectives on social structure.
Source: (Elder-Vass, 2010; Porpora, 2015).

Critical realism	Structuration theory
Structure is external to agents	Structure is internal to agents
Structure is the necessary, external relations between the constituents of social entities	Structure is internal rules and resources
Structure is objective	Structure is intersubjective
Social relations are prior to rule-following	Rule-following is prior to social relations
Behaviour is structured by social relations	Behaviour is structured by culture

"….We are dealing with a system of interlinked components that can only be defined in terms of the interrelations of each of them in an ongoing developmental process that generates emergent phenomena – including those we refer to as institutional structure. Emergent properties are therefore relational; they are not contained in the elements themselves and could not exist apart from them…" (Archer, 1982)

· These relations may be between the occupants of distinct social positions which in turn define their interconnections, resources, interests and incentives (e.g. between employer and employee) (Porpora, 1989). Or they may be between groups of people with shared expectations about what constitutes appropriate behaviour in different situations (e.g. between cyclist and car driver). While the first of these is more 'structural', and the second more 'cultural', they may both be understood as emergent properties of social entities. For example, Elder Vass (Giddens, 1984a) uses the term 'norm circle' to refer to the group of people committed to endorsing and enforcing a specific social norm. In each case, the relevant structural relationships predate individual action; enable, constrain and motivate (but do not determine) that action; give predictability to that action; and are either reproduced or transformed by that action. Critical realism therefore understands social structure as something external to individuals and deriving from temporal, spatial and intentional relations between those individuals – along with relevant physical artefacts (Elder-Vass, 2010; Elder-Vass,

Table 3
Sources of stability in sociotechnical systems.
Source: (Geels, 2004).

Source of stability	Stabilising mechanisms
Rules	Focus on particular types of engineering problem and solution; shared expectations; established roles and patterns of interaction; shared customs, values and norms; technical standards
Social groups	Interdependent relationships between different organisations; social relations and obligations; economic interests; political lobbying activities
Physical artefacts	Capital intensity and longevity of infrastructures; sunk investments; economies of scale; network externalities

2016). Both individual people and social structures have causal powers: the first through their agency (deployment of which requires interpretation, choice and strategy) and the second through encouraging, discouraging, enabling or constraining that agency (Jessop, 2005). Neither can be reduced to the other.

This arguably 'common-sense' view of social structure is very different from that proposed by structuration theory. For Giddens, structure exists entirely in people's heads:

> "…. Structure is….rules and resources, recursively implicated in the reproduction of social systems. Structure only exists in memory traces, the organic basis of human knowledgeability, and as instantiated in action……" (Giddens, 1984b)

> "….Structures exist in time-space only as moments recursively involved in the production of social systems. Structures have only a virtual existence…." (Giddens, 1981)

> "….Structures are not the patterned social practices that make up social systems, but the principles that pattern these practices……" (Sewell, 1992)

> "…[structure]… has no existence independent of the knowledge that agents have about what they do in their day-to-day activity." (Giddens, 1984b)

These passages are hard to interpret, but nevertheless serve to demonstrate that Gidden's interpretation of social structure is fundamentally different from the critical realist interpretation. The more conventional notion of social structure − namely relationships between people and social groups − forms part of Giddens theory but is labelled 'social system' instead:

> "….social systems are composed of patterns of relationships between actors or collectivities reproduced across time and space…" (Porpora, 1989).

However, these social systems have no causal properties of their own, but are instead 'structured' by the internal 'rules and resources' of participating actors. Causality derives not from the relationships between individuals and organisations within the social system, but from the repetitive rule-following behaviour of individuals. For Giddens, this internal, subjective behaviour is causally prior to the external reality of the social system; while for critical realists the reverse is the case (Table 4) (Porpora, 2015, 1989). As the critical realist author Margaret Archer argues (Archer, 2003, 1982), Giddens appears to conflate structure and agency and to equate the former with social practices.

As argued above, the concept of structure as 'internal rules' also underpins the MLP, whose core assumptions appears to be strongly influenced by structuration theory. This leads directly to the distinction between tangible sociotechnical systems (*cf* Giddens social system) and intangible sociotechnical regimes (*cf* Giddens rules and resources), and to the claims that regime rules: provide a 'deep structure' for sociotechnical systems; should be considered analytically prior to those systems; and provide the primary source of stability for those systems. As such, the limitations of Giddens structuration theory carry directly over into the foundational assumptions of the MLP, leading to an overemphasis on internal rules and an under-emphasis on external social relations.

These problems may also carry over into the empirical studies informed by the MLP. For example, many of these studies have emphasised cultural factors such as expectations, cultural meaning and user practices and paid less attention to physical and spatial constraints, material interests and economic incentives. This in turn has led several authors to criticise the MLP for its relative neglect of political power, and to propose ways in which power relations may be better integrated into the framework (Smith et al., 2005; Kern and Markard, 2016; Meadowcroft, 2009; Avelino and Rotmans, 2009). Such efforts could be handicapped, however, by the neglect of social and material relations within the foundational assumptions of the MLP, and the insistence instead upon the primacy of internal rules (Svensson and Nikoleris, 2018). Theories of power that depend upon a relational conception of social structure may be difficult to reconcile with a theory of transitions that depends upon an intersubjective conception of social structure − thereby creating the risk of tensions or inconsistencies.

However, the MLP does not appear to be wedded to structuration theory and also incorporates ideas from a range of other areas that make different assumptions about the relationship between structure and agency (Geels and Schot, 2010). The flexibility and malleability of the MLP, and it's constantly evolving nature, suggests that the theoretical primacy given to 'intangible' rules may be negotiable − especially since that primacy is not adhered to consistently within the MLP literature. In particular, many of the MLP case studies have a looser relationship to structuration theory than the more theoretical papers, and appear to give as much explanatory weight to material factors and social relations as to internal rules and norms.[12] It therefore appears possible to interpret many of the MLP case studies in a way that is consistent with a critical realist view of social structure, with its emphasis upon social relations and emergent causal powers. For example, the following passage from Geels − which immediately follows a mention of structuration theory − appears entirely compatible with a critical realist ontology that interprets structure as external relations rather than internal rules:

> "… Human agency, strategic behaviour and struggles are important but situated in the context of wider structures. Actors interact (struggle, form alliances, exercise power, negotiate and cooperate) within the constraints and opportunities of existing structures, at the same time that they act upon and restructure those systems. ….structures not only constrain but also enable action, i.e. make it possible by providing coordination and stability… " (Geels, 2004)

The MLP literature is also centrally concerned with the *artefactual* aspect of sociotechnical systems − something that has also been emphasised by critical realists (Elder-Vass, 2016; Gorski, 2016) but is largely missing from the sociological debate on agency and structure (including Giddens). This is crucial, since the physical constraints imposed by long-lived artefacts and infrastructures provide a primary explanation for the stability and inertia of sociotechnical systems (Table 3). This empirical focus, in turn, provides a strong motivation for abandoning a concept of social structure that undervalues material factors and constraints.

In addition, the MLP is continuously evolving and more recent publications place less emphasis on structuration theory and more upon other frameworks such as institutional theory (Fuenfschilling and Truffer, 2014) and political economy (Geels, 2014). For example, Geels and Schot (2010) note some weaknesses with structuration theory and highlight the 'morphogenetic approach' developed by a leading critical realist, Margaret Archer (1995, 2003). However, since Giddens' interpretation of social structure is incompatible with critical realism, it is inappropriate to use the latter to 'complement' the former − as Geels and Schot (2010) seek to do. Instead, what is needed is a more critical appraisal of the underlying assumptions of the MLP and a rejection of the confusing and unhelpful legacy of structuration theory. This in turn requires a rejection of the explanatory primacy given to sociotechnical regimes and a recognition that rules, social relations and material artefacts are interdependent and act in combination to give stability to a sociotechnical system (Table 3). This leads on to an alternative, critical realist interpretation of sociotechnical systems that rejects the distinction between systems and regimes − discussed further below.

[12] In a similar manner, Giddens introduces external structural constraints into his theoretical framework (termed 'structural properties'), but does not label these as social structure.

4.3. Boundaries and properties

A critical realist interpretation of the MLP could be that socio-technical systems constitute distinct entities, emergent from lower-level entities and with their own causal powers and liabilities. From this perspective, sociotechnical systems consist of multiple, lower-level entities (e.g. firms, technologies, infrastructures, norm circles) that are necessarily related in particular ways. These constituent entities, in turn, have their own causal powers and liabilities. The relations and interactions between these constituent entities allow the system to function effectively as a whole and provide it with causal properties that would not exist in the absence of those relations and interactions. A sociotechnical system therefore has properties and capabilities that cannot be predicted from the individual behaviour of its constituent entities, including both the stability of the system and the processes by which it maintains that stability and resists change. Hence, explanations of both stability and change that do not refer to the emergent properties of the system are necessarily incomplete.

This critical realist interpretation of sociotechnical systems appears broadly consistent with much of the empirical literature on the MLP. However, adopting this interpretation still leaves some practical difficulties.

First, sociotechnical systems have multiple properties and it is not clear which of these should be considered emergent and which should be considered as simply the aggregate outcome of one or more lower-level mechanisms − such as the increasing returns of technology adoption. For example, researchers using tools such as systems dynamics or agent-based modelling have shown how complex, aggregate patterns (including highly relevant phenomena such as path dependence and tipping points) may result from the interaction of constituent entities following relatively simple rules (Sterman, 2000; Miller, 2015).[13] Outcomes such as these are sometimes termed 'pattern' emergence to distinguish them from the 'ontological' emergence required for the definition of a social entity (Gorski, 2016). A key question for the MLP therefore, is whether such 'reductionist' explanations are sufficient to explain observed phenomena, or whether they can only be explained by the emergent properties of a sociotechnical system. If the former is the case, the sociotechnical system may neither be a distinct social entity nor be required for causal explanation.

Second, for the ontological status of sociotechnical systems to be adequately defended, it would be necessary to identify: the constituent *parts* (entities) of the relevant system; the necessary *relationships* between those parts; the emergent causal *properties* of the system; the *processes* through which the constituent parts and relationships produce those causal properties; and the *processes* through which the system becomes established and is maintained (Elder-Vass, 2010). This in turn would require a clear definition of the societal *function(s)* that the system fulfils. But such a systematic approach is challenging − and the existing MLP literature falls short in a number of respects.

One fundamental problem is that the functional *boundaries* of individual sociotechnical systems, as well as the *societal functions* they fulfil, are typically left rather vague. For example, does the car-based transport system deliver the societal function of mobility, or car-based mobility or accessibility to particular destinations? Both mobility and accessibility are also delivered by other technologies and systems that share many elements with the car-based transport system, but also differ from it in important ways. Bus transport, for example, also requires a road network, together with associated rules (e.g. highway code) and organisations (e.g. highway maintenance) and is equally reliant upon the global oil industry and associated infrastructures, together with the knowledge and skills associated with motor manufacturing. So should bus transport be considered as part of the sociotechnical system of 'automobility', or a subsystem or a separate system? Similarly, cycle transport shares the road network together with the rules and norms of road use, and the latter also govern the interactions between cars and cycles. Hence, there may be nested and overlapping sociotechnical systems in different areas. But the criteria for identifying whether particular entities should be included or excluded from a system; whether particular relationships are necessary or contingent to the functioning of that system; and whether particular causal properties should be attributed to that system, a subset of that system or to something else remains poorly specified. For example, the oil industry is necessary for the functioning of car-based transport system and is also affected by actors within that system. But it is not clear whether it should be considered part of the automobility system or part of the broader landscape.

In a similar manner, a sociotechnical transition may transform some parts of a system (e.g. industrial supply chains, knowledge and skills associated with engine manufacture) while leaving many other parts unchanged (e.g. road networks, highway codes, user practices). At the same time, technological and social changes may drive transitions within several systems simultaneously (e.g. the use of fuel cells for both car and bus transport, or the use of self-driving technologies for all forms of transport) and subsystems that are already well-established (and hence not niche) may gradually displace 'higher level' systems (e.g. mass transit displacing car travel). Similar ambiguities occur in relation to the temporal boundaries of a sociotechnical transition. As Genus and Coles (2008) observe, the MLP does not provide clear criteria for defining when a transition begins or ends, and different studies appear to employ different criteria − even when studying the same transition. While such complexity could be considered an inherent feature of the social world, the looseness of the 'sociotechnical system/regime' and 'sociotechnical transition' concepts make the choice of functional, spatial and temporal boundaries appear rather arbitrary − thereby potentially reducing the MLP's explanatory power. This has implications, for example, for evaluating whether properties such as stability, resilience and inertia should be considered 'ontologically emergent' properties of a sociotechnical system, or merely 'pattern emergent' outcomes of a limited number of lower-level mechanisms, such as increasing returns. If the latter is the case, the concept of a sociotechnical system may not be necessary for causal explanation.

These ambiguities over the boundaries of sociotechnical systems − or regimes − are further complicated by the claims that sociotechnical regimes coordinate developments within several *sub-regimes* in areas such as science, technology, industry, policy, culture and markets (see Fig. 1) (Geels, 2002a, 2004). Rules within these sub-regimes are said to be aligned with each other. For example, scientific and engineering knowledge about internal combustion engines (science sub-regime) is aligned with the rules governing the organisation of the car industry and its associated supply chains (industry sub-regime) (Geels, 2004). But the science, industry and other 'sub regimes' both extend to and affect multiple other sociotechnical regimes. Hence, there are blurred boundaries between different sub-regimes as well as between different sociotechnical regimes/systems. This creates confusion, along with the risk that causal mechanisms will be attributed to one level or to one regime/system, whereas in fact they belong to a different level or regime/system, or to the external landscape.

In sum, the MLP rests upon a problematic interpretation of social structure that is inconsistent with the ontology of critical realism and encourages a neglect of social relations, material interests and political power. From a critical realist perspective, it would be better to drop the distinction between systems and regimes altogether and to interpret and explain the former as a distinct social entity with emergent causal properties. But that still leaves a number of difficulties, particularly in relation to the ambiguous temporal, spatial and functional boundaries of sociotechnical systems and the extent to which the concept is necessary for causal explanation. The next section will investigate

[13] For example, in a classic study, Schelling (Schelling, 1971) showed how extreme levels of racial segregation could result from individuals exercising relatively 'mild' preferences about neighbourhood choice.

whether there are similar tensions between the implicit epistemology of the MLP and critical realism and whether this leads to similar difficulties.

5. Sociotechnical epistemology and methodology

MLP case studies are complex, descriptive, qualitative and multi-dimensional and therefore very different from the parsimonious, comparative and quantitative studies that dominate in areas such as economics. As a result the MLP provides little that would be recognised as 'theory-testing' by researchers from more positivist research traditions − characterised, for example, by parsimony, a focus upon measurable variables, a search for regularities across space and time and the use of quantitative research methods. This leads sociotechnical ideas to be resisted or neglected by such researchers, including many who work on innovation. While this tension derives in part from the MLP's focus on highly complex processes operating at multiple levels over the long-term, it also reflects more fundamental disagreements about the status of social scientific knowledge, the processes through which such knowledge can be produced and the criteria by which it should be justified (i.e. epistemology). As with ontology, the implicit epistemology of the MLP has several affinities with critical realism, since both reject the core assumptions of positivism (Table 1). But there are also a number of important tensions.

5.1. Heuristics and explanations

For critical realists, the objective of studying sociotechnical transitions should be to *explain* their sequence and outcomes in terms of complex and contingent conjunctions of social entities and their associated causal powers (Steinmetz, 2004). This involves conceptualising and describing the relevant entities and powers and investigating how they combine to produce the observed outcomes (Danermark et al., 2001).

In part, this is what MLP case studies seek to do. For example, in his study of the transition from horse-drawn carriages to automobiles, Geels (2005a) highlights a remarkably wide range of causal mechanisms including: the increasing returns from technology adoption; political lobbying and strategic coalitions by groups with shared interests (e.g. car, construction and cement companies); and path dependencies, such as gasoline cars building upon the existing fuel infrastructure for agricultural vehicles. Although these processes and mechanisms tend towards certain outcomes, there is contingency in how, when and in what way they combine, what the resulting outcomes are and how external 'landscape' changes affect those outcomes (although it is not clear whether something like suburbanisation should be considered part of the landscape or part of the system).

However, the MLP studies do not emphasise causal explanation in the same way or to the same extent as critical realism. Frequently, the MLP is described as a 'heuristic device' − a rather ambiguous term, defined in the dictionary of sociology as "…any procedure which involves the use of an artificial construct to assist in the exploration of social phenomena" (Scott and Marshall, 2009). An artificial construct is not the same as the real entities and mechanisms that critical realists seek to uncover − and this difference is reflected in accounts of how the MLP is used:

> "….Frameworks such as the MLP are not 'truth machines'… instead they are 'heuristic devices' that guide the analyst's attention to relevant questions and problems. Their appropriate application….help the analyst 'see' interesting patterns and mechanisms…." (Geels, 2012)

> "… [heuristic perspectives] identify the relevant variables and the questions… All the interactions among the variables and the frameworks cannot be rigorously drawn. The frameworks, however, seek to help the analyst to better think through the problem…" (Porter (1991), quoted in Geels (2011))

Hence, while MLP case studies identify a wide range of causal mechanisms, the overall framework − and thereby the core claims regarding the necessity of alignment between different mechanisms − appears very 'loose'. One consequence of this looseness is that the MLP is remarkably adaptable. It has been applied to historical transitions as varied as the transition from sailing to steam ships (1780–1900) (Geels, 2004), the transformation of US factory production (1850–1930) (Geels, 2006b) and the breakthrough of rock 'n' roll (1930–1970) (Geels, 2007). Similarly, emerging 'sustainable' niches have been conceptualised as narrowly as car sharing (Ornetzeder and Rohracher, 2013) and as widely as renewable electricity (Verbong and Geels, 2007). Given the wide variations in spatial and temporal boundaries of sociotechnical systems, the nature of the core (social or technical) innovations in these systems and the relevant socio-economic contexts, one would expect these case studies to reveal significant differences in the nature and relative importance of different causal mechanisms. But the framework claims to account for them all.

When the evidence indicates the limitations of the standard 'niche breakthrough' model outlined in Section 2 (Fig. 1), the MLP is modified to accommodate: for example by postulating alternative transition pathways (e.g. transformation, reconfiguration, technological substitution, de-alignment/re-alignment, step-wise adjustment) (Geels, 2006b; Geels and Schot, 2007), or by highlighting variations and linkages between different spatial scales (Raven et al., 2012). Hence, the MLP is neither compared to nor tested against other theories, but instead continuously elaborated to accommodate evidence from different case studies. This would appear to make it closer to a heuristic device, or to a loose organising framework, than to an explanatory theory − with the weight of causal explanation resting instead upon 'lower-level' mechanisms such as learning processes and the economic decisions that contribute to path dependence, as well as upon contingent sequences of events. But if that is the case, it weakens the argument that a sociotechnical system should be considered an emergent and causally significant entity that 'aligns' different processes, and that the interactions between niche, regime and landscape are a necessary condition for a transition to occur. Or more fundamentally, it weakens the argument that causal explanation requires the concept of a sociotechnical system at all.

5.2. Necessity and contingency

One way of understanding the MLP is to consider how it employs the different modes of scientific inference summarised in Table 5 (Danermark et al., 2001). *Deduction* and *induction* are the most familiar, but are insufficient for scientific practice since the former provides no knowledge of reality beyond the initial premises and the latter provides no knowledge of underlying structures and mechanisms. They must therefore be supplemented by *abduction* and/or *retroduction* − which aim to reinterpret empirical observations in the context of more general ideas:

> "…Abduction is the process of forming an explanatory hypothesis and is the only logical operation which introduces any new idea….Deduction proves that something must be; Induction shows that something actually is operative; Abduction merely suggests that something may be…" (Hartshorne and Weiss, 1958)

The MLP relies primarily upon *abduction* − namely, reinterpreting a set of empirical observations in the light of a particular theoretical framework, with the aim of discovering connections and relations between those observations (Danermark et al., 2001). This is similar to a doctor inferring the presence of the disease from a group of symptoms, but provides no ultimate way of deciding whether the framework is valid. While a doctor may consider several possible diseases, empirical studies using the MLP consider only a *single* overarching framework, but

Table 5
Modes of scientific inference.
Source: (Danermark et al., 2001).

	Deduction	Induction	Abduction	Retroduction
Structure	Deriving logically valid conclusions from given premises	Deriving universally valid conclusions about a population from a number of observations	Interpreting and re-contextualising phenomena within a conceptual framework or set of ideas.	Reconstructing the conditions for the observed phenomena to be what they are.
Issue	What are the logical conclusions of the premises	What factor(s) common to observed entities are also true of a larger population	What meaning is given to something interpreted within a particular conceptual framework	What qualities must exist for something to be possible
Strength	Guides logical derivations and assessments of validity	Guides empirical generalisations	Guides interpretation of the meaning of events in relation to a larger context	Guides interpretation of underlying structures and mechanisms that cannot be directly observed
Limitations	Does not say anything new about reality beyond what is in the premises	Risk of drawing the wrong conclusion (black swans), unable to produce knowledge of underlying structures and mechanisms	No fixed criteria to assess the validity of the conclusions	No fixed criteria to assess the validity of the conclusions
Required skills	Logical reasoning ability	Statistical ability	Creativity and imagination	Ability to abstract

with variations in the relevant processes and the way in which they combine. Relatively little use is made of deduction or induction.

In contrast, critical realism emphasises the importance of *retroduction* − a term that, along with abduction, was first introduced by Pierce (Danermark et al., 2001; Hartshorne and Weiss, 1958). Although there is considerable ambiguity in the use of these terms, their Latin roots (*ab* = leading away from, *retro* = deliberately leading backwards) indicate that: "… retroduction is a deliberate and recursive process involving more than the making of an abductive inference…" (Chiasson, 2005). Within critical realism, retroduction is interpreted as: a) taking a set of empirical observations and proposing hypothetical mechanisms that, if they existed, would generate or cause those observations; and b) choosing between these mechanisms (or identifying the most likely combination of mechanisms) based on their ability to describe the necessary conditions for the observed phenomena (Bhaskar, 2014; Mingers, 2004). Precisely *how* this should be done is inadequately discussed within the critical realist literature, which tends to be much stronger on ontology than on epistemology and methodology.[14] But it commonly involves asking 'characteristically realist questions' such as: What makes X possible? What properties must exist for X to be what it is? What does the existence of this object or practice presuppose? Could object A exist without B? (Sayer, 1992). A key feature of this process is the assessment of whether particular entities, mechanisms and causal powers are *necessary* to explain the observations or merely *contingent* to those observations (Sayer, 1992).

This emphasis on necessity and contingency appears to be lacking within the MLP literature, which exhibits a tendency to include an increasing number of mechanisms and ideas within the overarching framework (Geels, 2017). This is evident in the multiple extensions and modifications to the MLP and in the numerous proposals for 'enriching' the MLP with different theoretical ideas. The MLP began life as a highly ambitious synthesis of evolutionary economics, science and technology studies, structuration theory and neo-institutional theory (Geels, 2002a), but has since been supplemented (or proposed to be supplemented) with ideas from political economy (Smith and Stirling, 2010), political ecology (Lawhon and Murphy, 2012), political science (Geels, 2014), reflexive governance (Smith and Stirling, 2007), multilevel governance (Bulkeley et al., 2010), cultural sociology (Swidler, 1986), discourse analysis (Geels and Verhees, 2011), geography and regional studies (Coenen et al., 2012; Murphy, 2015; Calvert et al., 2017; Raven et al., 2012), psychology (Bögel and Upham, 2018), social movement theory (Elzen et al., 2011), dynamic capabilities (Teece et al., 1997), ambidextrous organisations (Tushman and O'Reilly, 1996) and numerous other areas.

There are drawbacks to this trend. First, the breadth of ideas is sufficiently wide that only a particularly talented researcher could hope to employ even a subset of them within a single empirical study. Second, the ratio of theoretical propositions to available evidence is likely to be unworkable, particularly when relying solely upon secondary data. Third, the trend to add to rather than subtract from the framework neglects the possibility that many processes and mechanisms could be of secondary or no importance in particular transition processes, and may therefore be ignored in those cases. Fourth, the inclusion of an increasing number of theoretical ideas complicates the validation of individual propositions. As Kirser observes: "… It is very difficult to test the validity of a narrative containing loosely connected bits of arguments from a variety of theories…" (Kiser, 1996)

As an example, consider Geels (Geels, 2006b) account of the electrification of US factory production, which involved the stepwise

[14] Reference is commonly made to choosing between theories on the basis of their relative 'explanatory power', but this criteria has proved difficult to define and operationalise (Robert Isaksen, 2016). For example, Bhaskar provides the rather vague suggestion that: "… A theory T_c is preferable to a theory T_d… provided that T_c can explain under its descriptions, almost all the phenomena that T_d can explain under its descriptions, plus some significant phenomena that T_d cannot explain."(Bhaskar, 1975).

Table 6
Process versus variance theories.
Source: (Poole et al., 2000; Van de Ven and Poole, 2005).

Variance approach	Process approach
Fixed entities with varying attributes. Variables do the acting	Entities participate in events and change identity over time. Actors do the acting
Attributes a single meaning over time	Entities, attributes and events may change in meaning over time
Time ordering among independent variables is immaterial	Time ordering of events is critical
Generality depends on uniformity across contexts (laws)	Generality depends on versatility across cases (variations within overall patterns)

integration of a series of innovations in machine tools, building materials, materials handling technologies, power generation, power distribution, lighting and other areas. As with many MLP studies, this is an insightful, wide-ranging and richly descriptive account of multiple developments at the niche, regime and landscape levels. However, it gives little consideration to whether particular events and processes were *necessary* for the transition to occur − or why it occurred first in the US. For example, it could be argued that several of the highlighted developments − such as the professionalization of engineers, laissez-faire economic policies, cultural enthusiasm for electricity, the use of electric trams in cities, the rise of the 'efficiency' movement − were *secondary* developments and hence not necessary for the transition to occur. But Geels' narrative provides no way of assessing the necessity or contingency of those events and processes, or whether one should be considered more important than another. In other words, instead of seeking ways to test the relevance and importance of different mechanisms and events, their importance tends to be implied by their inclusion in the narrative. Similarly, the necessity of 'alignment' between all of the different mechanisms appears as an *a priori* assumption rather than a testable hypothesis.

Methods for dealing with such limitations are widely used within the social sciences (George and Bennett, 2005), but rarely within transition studies. One approach is to develop *counterfactuals*, with the aim of assessing whether the absence or modification of a particular event or process would have led to a significantly different outcome. Although such exercises are necessarily hypothetical, much can be learned by systematically thinking through the theoretical and empirical issues involved (Danermark et al., 2001; Griffin, 1993). For example, Fearon argues that: "… the common condition of too many variables and too few cases makes counterfactual thought experiments necessary means for justification of causal claims…" (Fearon, 1991) A key difficulty with developing counterfactuals for MLP case studies, however, is that causality is assumed to result from multiple mechanisms and events that combine in different ways over very long periods of time. This combination of interdependence and sequence makes counterfactuals hard to construct (George and Bennett, 2005).

An alternative and more promising approach would be to *compare* two or more case studies: for example, investigate the electrification process in another context where particular conditions or processes were not present or in a context where they were present but the transition was delayed or the outcomes were different (Fearon, 1991; Lijphart, 1975). Although most comparative methods derive from positivist research traditions, their use is compatible with critical realism (Lawson, 1997; Steinmetz, 2004; Griffin, 1993; Lawson, 2001). But again, since the spatial and temporal scope of sociotechnical transitions is greater than in most social scientific research, the application of comparative methods is challenging. One could conduct cross-country comparisons, but the number of relevant differences at the niche, regime and landscape levels makes this difficult.

A third approach would be to investigate the potential for agent-based or system dynamic *modelling* of transition processes (Papachristos, 2014; Safarzyńska et al., 2012; Holtz et al., 2015). Although these are reductionist tools, they can also incorporate some of the structural factors that enable and constrain behaviour, together with learning processes. Hence, these could potentially deliver useful insights into the dynamics of transitions, including whether bottom-up processes are sufficient to explain at least some of the observed outcomes. While McDowall and Geels (2017) express scepticism about the utility of such tools for studying transitions, their argument rests in part upon the ontological and epistemological assumptions that are criticised in this paper. McDowall and Geels are correct, however, in arguing that the complexity, scope, duration and multi-dimensionality of sociotechnical transitions present a considerable challenge − and more generally, stretches the bounds of feasible causal explanation.

5.3. Processes and narratives

Another way of understanding the MLP is to view it as a 'process' rather than a 'variance' theory (Table 6). This distinction derives from the work of organisational theorists such as Poole et al. (2000) and Abbott (2001):

> "…There are two ways of seeing….historical processes more generally. One focuses on stochastic realisation and aims to find causes; the other focuses on narratives and aims to find typical patterns…"(Abbott, 2001)

The second of these approaches has influenced the MLP:

> "….the MLP employs 'process theory' as explanatory style rather than 'variance theory'….Process theories do not explain variance in the dependent variable as 'caused' by independent variables, but instead explain outcomes in terms of event sequences and the timing and conjunctures of event-chains….Depending on the research topic and question, these can be micro-events such as moves and countermoves by actors, or they can be macro-events …." (Geels, 2011)

Process theory sees the world as comprised of 'entities' that participate in 'events', although the interpretation and use of these terms differs from critical realism (Poole et al., 2000; Van de Ven and Poole, 2005). Explanation then depends upon identifying critical events and conjunctions of events. The focus is on temporal sequences − how one event leads to and influences subsequent events. But this implies that process theory focuses upon the *empirical* level rather than *real* structures and mechanisms. Events are relevant to causal explanation, but for critical realists a focus upon events alone is insufficient. For example, the introduction of supportive regulations (an event) may have accelerated the diffusion of cars, but to fully understand and explain this event (why did it happen?) and its consequences (why did it have these results?), it is necessary to dig deeper and identify the nature and mode of operation of the underlying structures and mechanisms − such as the motivations and resources of different interest groups, the processes of coalition formation and lobbying, the opportunities and constraints provided by the relevant political structures and the incentives faced by decision-makers. As Lawson notes[15]:

> "….the world is composed not only of 'surface phenomena' such as skin spots, puppies turning into dogs, and relatively slow productivity growth in the UK, but also of underlying and governing structures and mechanisms such as … viruses, genetic codes and the British system of industrial relations …." (Lawson, 1997)

[15] Similarly, Porpora observes: "… Critical realism does not completely rule out talk of events causing other events. In the event that the baseball, flying through the air, breaks a window, it could be said that the one event caused the other. But more fundamental than events are the ontological particulars involved….and their causal properties. It is the hardness of the ball, its projectability, and its momentum that gives it the power to break, and the brittleness of the window that disposes it to breaking… In each case the causal powers of the particular derive from its essential properties which in turn derive from its internal structure…" (Porpora, 2015).

Indeed, despite the influence of process theory, the MLP case studies do highlight multiple interacting causal mechanisms of this type. The problem is more the explanatory status of these *vis a vis* both event sequences and the overarching theoretical framework – with the latter appearing to take priority over the former.

The MLP has also been termed a form of 'narrative explanation' (Geels, 2011; Griffin, 1993; Abbott, 2001; Abell, 2004) – a term used within historical sociology that has many similarities with process theory:

> "… narrative explanations take the form of an unfolding, open-ended story fraught with conjunctions and contingency, where what happens, an action, in fact happens because of its order and position in the story. Narrative therefore permits a form of sequential causation that allows for twisting, varied and heterogeneous time paths to a particular outcome …" (Griffin, 1993)

Narrative explanations combine description with interpretation, but their informality can make it very difficult to assess either the significance of different events or the comprehensiveness of the account. This problem can be mitigated through the use of more formal techniques such as event-sequence analysis (Abbott, 1995; Abbott, 1992), but these still focus upon events rather than underlying mechanisms. An alternative is event-structure analysis which "… forces the analyst to replace temporal order with her or his expert judgement or knowledge about causal connections…" (Griffin, 1993). However, these formal techniques have not been applied to transition studies and the scale and complexity of the processes involved could make this difficult to do. Instead, causality is sought in the overall 'plot' provided by the MLP:

> "….To develop causal narratives, explanations need be guided by 'heuristic devices' such as conceptual frameworks that specify a certain plot….The multi-level perspective provides such a plot for the study of transitions.…Although the specific event sequences of each (transition) are different, process theories such as…the MLP can claim versatility or generality when they are able to identify recurring causal patterns…." (Geels, 2011)

> "….In process theory, the generality of explanations depends upon their versatility, the degree to which they can encompass a broad domain of developmental patterns without modification of their essential character. The broader its domain (the greater the variety of cases, contacts, events and patterns the theory can adapt to), the more general the explanation…." (Geels and Schot, 2010)

In this formulation, the success of an empirical narrative lays not so much in the identification of operational causal mechanisms, but in the extent to which it can be interpreted in the light of a highly versatile theoretical framework that provides a 'guiding plot'. But this provides no confidence that the plot is correct, that the narrative includes the most important factors and events (and excludes the unimportant or irrelevant ones), or that the causal mechanisms operating in particular cases or at particular points in time have been adequately identified and understood. Using versatility as a criterion for success creates the risk that the theory simultaneously explains everything and nothing. In practice, one would expect social entities and practices to be bounded in space and time. Transitions entail structural changes both within and between social entities, so the relevance and relative importance of different causal mechanisms may be expected to change over time and between different situations. Good explanations may therefore be complex, contingent and specific, rather than universalising and the causal importance of postulated entities such as the sociotechnical system/regime, or particular processes such as the development of expectations, needs to be demonstrated rather than assumed.

In sum, the implicit epistemology of the MLP has more in common with critical realism than with positivism, but there are important tensions between the two. As with the ontological tensions discussed in Section 4, these derive as much from the ambition of the MLP to explain extremely complex processes that unfold over many decades as they do from its reliance upon particular assumptions or methodological tools. And as with the implicit ontology of the MLP, there may be sufficient flexibility in the framework to accommodate adjustments to make it more compatible with critical realism.

6. Summary

This paper has sought to identify the foundational assumptions of the MLP and to assess their consistency with critical realism. In contrast to most studies in this area, the aim has not been to 'enrich' the MLP with new theoretical ideas, or to apply the MLP to a new empirical topic, but instead to draw attention to some of the strengths and weaknesses of its underlying philosophical assumptions. This has been achieved by comparing the implicit ontology and epistemology of the MLP to that of critical realism, and by making some suggestions for reducing the tensions between the two.

With regard to ontology, the MLP has been criticised for relying upon a problematic conception of social structure that is inconsistent with critical realism and which encourages a neglect of material interests and political power. This has contributed to the ambiguous and unhelpful distinction between systems and regimes and to the questionable priority given to intersubjective rules over social relations. Progress could be made by dropping the concept of sociotechnical regimes altogether and focusing solely upon the nature, structure and properties of sociotechnical systems. This, however, would require greater clarity about: the empirical boundaries of different sociotechnical systems; whether particular components, relationships and properties are necessary or contingent features of those systems; and whether particular causal properties are emergent features of those systems or simply the patterned outcome of 'lower-level' mechanisms such as increasing returns. That clarity is lacking from much of the MLP literature which also exhibits a tendency to assume rather than demonstrate that the concept of a sociotechnical regime/system is required for causal explanation.

With regard to epistemology and methodology, both the MLP and critical realism share a rejection of the core assumptions of positivism, including the priority given to quantitative methods. But the application of the MLP creates a number of difficulties, including: a) the tendency to use the framework as a heuristic device rather than the basis of causal explanation; b) the priority given to this overarching theoretical framework, as compared to testing competing theories or assessing the relative importance of different causal mechanisms; c) the lack of attention to the necessity or contingency of particular mechanisms or events; d) the reliance upon single, historical case studies with limited use of comparative case studies or other research methods; e) the influence of 'process theory' that emphasises empirical events rather than underlying structures and mechanisms; and f) the scepticism towards more 'reductionist' methodologies such as agent-based and systems dynamics modelling that could potentially offer useful insights into specific transition processes.

However, the MLP is both highly flexible and continuously evolving and could therefore be modified in ways that reduce each of the above difficulties. There are at least three priorities for future research:

First, reflect more upon the philosophical assumptions underpinning the MLP, rather than elaborating an already over-complex theoretical framework. The tendency to add further dimensions and ideas runs the risk of making the MLP unworkable, especially when those ideas derive from contradictory philosophical traditions.

Second, shift attention away from the framework itself and towards identifying the specific causal mechanisms that drive particular transitions. The priority should be to demonstrate the necessity or contingency of specific mechanisms and events, rather than assuming that alignment of a range of these is required for a transition to occur. The complexity of transitions makes this very difficult to do, but progress could be made through the greater use of comparative case studies

(either historical or contemporary) and quantitative modelling tools.

Third, drop the distinction between the systems and regimes since this is confusing and ambiguous, is interpreted in different ways by different authors and is based upon a highly questionable interpretation of social structure that downplays the importance of physical artefacts, material interests, economic incentives and political power. The unhelpful distinction between system and regime is a legacy of Giddens' structuration theory and is best abandoned. Critical realism provides a much better understanding of social structure and allows sociotechnical systems to be interpreted as emergent entities whose causal properties derive from the necessary relationships between their constituent parts. These include rules and norms (the regime), but those rules and norms depend in turn upon material and social relations (the system). Given this interdependence it would be more appropriate to use a *single* term to refer to both.

Given the complexity of the relevant issues and the strength of adherence to particular philosophical assumptions, these theoretical suggestions are likely to encounter resistance from MLP researchers. For example, after 15 years of arguing for the primacy of intersubjective rules, the distinction between systems and regimes is not going to be easily abandoned. Similarly, since the success of the MLP stems in part from the 'looseness' of the overarching framework and the stimulus this provides to new ideas, a proposal to narrow the focus could be seen as obstructive and unhelpful. And given the complexity and temporal/spatial scope of transition processes, both comparative case studies and simulation modelling could prove very challenging to conduct. Nevertheless, the philosophical assumptions underlying the MLP deserve to be questioned − and it is possible that the alternative, critical realist perspective outlined here could lead to a more robust understanding of the nature and causes of sociotechnical transitions.

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