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From sectoral systems of innovation to socio-technical systems Insights about dynamics and change from sociology and institutional theory

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Abstract

In the last decade 'sectoral systems of innovation' have emerged as a new approach in innovation studies. This article makes four contributions to the approach by addressing some open issues. The first contribution is to explicitly incorporate the user side in the analysis. Hence, the unit of analysis is widened from sectoral systems of innovation to socio-technical systems. The second contribution is to suggest an analytical distinction between systems, actors involved in them, and the institutions which guide actor's perceptions and activities. Thirdly, the article opens up the black box of institutions, making them an integral part of the analysis. Institutions should not just be used to explain inertia and stability. They can also be used to conceptualise the dynamic interplay between actors and structures. The fourth contribution is to address issues of change from one system to another. The article provides a coherent conceptual multi-level perspective, using insights from sociology, institutional theory and innovation studies. The perspective is particularly useful to analyse long-term dynamics, shifts from one socio-technical system to another and the co-evolution of technology and society.
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Keywords: Sectoral systems of innovation; Institutional theory; Regime shifts; Multi-level perspective; Co-evolution

1. Introduction

In the last decade 'systems of innovation' has emerged as a new topic on the research agenda of innovation studies. It has opened up a promising strand of study, in which the scope of analysis has been broadened from artefacts to systems, from individual organisations (often firms) to networks of organisations. Systems of innovation can be defined on several levels (e.g. national, sectoral, regional). This paper makes a contribution to the level of sectoral systems. At this level there are several approaches, which describe the systemic nature of innovation, albeit with a slightly different focus, e.g. sectoral systems of innovation (Breschi and Malerba, 1997; Malerba, 2002), technological systems (Carlsson and Stankiewicz, 1991; Carlsson, 1997) and large technical systems (Hughes, 1983, 1987; Mayntz and Hughes, 1988; La Porte, 1991; Summerton, 1994; Coutard, 1999). I will briefly describe the thrust of these three approaches. A *sectoral system of innovation* can be defined as:

> a system (group) of firms active in developing and making a sector's products and in generat-

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> ing and utilizing a sector's technologies; such a system of firms is related in two different ways: through processes of interaction and cooperation in artefact-technology development and through processes of competition and selection in innovative and market activities
>
> (Breschi and Malerba, 1997, p. 131).

Although this definition includes the selection environment, it does not explicitly look at the user side. Furthermore, the definition mainly looks at firms, neglecting other kinds of organisations.

A *technological system* is defined as:

> ... networks of agents interacting in a specific technology area under a particular institutional infrastructure to generate, diffuse and utilize technology. Technological systems are defined in terms of knowledge or competence flows rather than flows of ordinary goods and services. They consist of dynamic knowledge and competence networks
>
> (Carlsson and Stankiewicz, 1991, p. 111).

This definition highlights more explicitly the importance of not only understanding the *creation* of technology, but also its diffusion and *utilisation.* On the other hand, technological systems seem to be narrowed down to social systems ('networks of agents'). Although actors are important, the material aspects of systems could be better conceptualised.

The material aspect of systems is central in the *Large Technical Systems* (LTS) approach. LTS refer to a particular kind of technology involving infrastructures, e.g. electricity networks, railroad networks, telephone systems, videotex, internet. The LTS approach not only has a specific unit of analysis, but also developed a particular mode of analysis, looking at socio-technical 'seamless webs' and system builders (Hughes, 1983, 1986, 1987). Among the components of LTS are physical artifacts (such as turbo-generators, transformers, electric transmission lines), but also organisations (e.g. manufacturing firms, investment banks, research and development laboratories), natural resources, scientific elements (e.g. books, articles), legislative artifacts (e.g. laws) and university teaching programs (Hughes, 1987, p. 51). System builders travel between domains such as economics, politics, technology, applied scientific research and aspects of social change, weaving a seamless web into a functioning whole. New technologies and the user environment are constructed in the same process.

These three approaches share an emphasis on interlinkages between elements, and they all see innovation as co-evolutionary process. But there are some differences regarding the kinds of elements involved in systems and their relationships. The aim of this paper is to contribute to the discussion about the kinds of elements and, especially, the dynamic interactions between them. These contributions focus on four points.

The first contribution is to include both the supply side (innovations) *and* the demand side (user environment) in the definition of systems. The sectoral systems of innovation approach has a strong focus on the *development* of *knowledge*, and pays less attention to the *diffusion* and *use* of *technology*, impacts and societal transformations. Sometimes, the user side is taken for granted or narrowed down to a 'selection environment'. Hence I propose a widening from sectoral systems of innovation to socio-technical systems. This means that the fulfilment of societal functions becomes central (e.g. transport, communication, materials supply, housing). This indicates that the focus is not just on innovations, but also on use and functionality. The need to pay more attention to innovation *and* users has, in fact, already been identified by a range of scholars in innovation studies and evolutionary economics. So the paper aims to link up with an identified 'open issue' in the field.

Second, with regard to the kinds of elements I will propose to make an analytic distinction between: systems (resources, material aspects), actors involved in maintaining and changing the system, and the rules and institutions which guide actor's perceptions and activities. I suggest such analytical distinctions are useful because some current literatures group together too many heterogeneous elements. For instance, Malerba (2002), pp. 250–251, wrote that "the basic elements of a sectoral system are: (a) products; (b) agents: firms and non-firm organisations (such as universities, financial institutions, central government, local authorities), as well as organisations at lower (R&D departments) or higher level of aggregation (e.g. firms, consortia); individuals; (c) knowledge and learning processes: the knowledge base of innovative and production activities differ across sectors and greatly affect the innovative activities, the organisation and the behaviour of firms and other agents within a sector; (d) basic technologies, inputs, demands, and the related links and complementarities: links and complementarities at the technology, input and demand levels may be both static and dynamic. They include interdependencies among vertically or horizontally related sectors, the convergence of previously separated products or the emergence of new demand from existing demand. Interdependencies and complementarities define the real boundaries of a sectoral system. They may be at the input, technology or demand level and may concern innovation, production and sale. The (d) mechanisms of interaction both within firms and outside firms: agents are examined as involved in market and non-market interactions; (e) processes of competition and selection; (f) institutions, such as standards, regulations, labour markets, and so on". Although these elements are all important, it is somewhat unclear how they are linked. This article aims to make progress on this issue.

The third contribution links up with another 'open issue', which has also been identified in the field, i.e. to pay more attention to institutions. Sometimes institutions are a 'left-over category' in analyses. It also happens that institutions are wrongly equated with (non-market) organisations. See, for instance, Reddy et al. (1991), p. 299, "examples of non-market institutions include: professional societies, trade associations, governmental agencies, independent research and coordination organisations, and public-service organisations". Anyway, there is a recognised need to better conceptualise the role of institutions in innovation. In particular, it is useful to explain how institutions play a role in *dynamic* developments, rather than explaining inertia and stability.

A fourth contribution of the article is to address the *change* from one system to another. This is relevant, because the main focus in the systems of innovation approach has been on the *functioning* of systems (e.g. a static or comparative analysis of the innovative performance of countries). If there was attention for dynamics, it was usually focused on the *emergence* of new systems or industries (e.g. Rosenkopf and Tushman, 1994; Van de Ven, 1993). Not much attention has been paid to the change from one system to another. In a recent discussion of sectoral systems of innovation Malerba (2002), p. 259, noted that one of the key questions that need to be explored in-depth is: "how do new sectoral systems emerge, and what is the link with the previous sectoral system?" This question is taken up in the article. This means the focus of the article is not on (economic) performance, but on dynamics and change.

These four contributions are made by describing a coherent conceptual perspective. This means the paper is mainly conceptual and theoretical, using insights from different literatures. Insights from sociology of technology and institutional theory are combined with innovation studies, science and technology studies, cultural studies and domestication studies. Section 2 proposes to widen the focus from systems of innovation to socio-technical systems. The kinds of elements are described, as well as the different actors and social groups which carry and (re)produce socio-technical systems. Section 2 also describes the basic conceptual framework where systems, actors and institutions/rules are seen as three interrelated dimensions. Section 3 opens up the black box of institutions. To avoid confusion of institutions with (public) organisations, the general concept of rules is proposed. Using sociology and institutional theory, different kinds of rules are distinguished (cognitive, normative and formal/regulative) with different effects on human action. Section 4 returns to the three dimensions of systems, actors and rules, and focuses on dynamic interactions over time. A dynamic sociological conceptualisation is developed which understands human action as structured, but leaves much room for intelligent perception and strategic action. The crucial point is to make the framework dynamic, i.e. indicate how economic activities and processes may influence and transform the sociological structures in which they are embedded. The fourth contribution is made in Section 5, which deals with stability and change of socio-technical systems. To understand stability, literatures on path dependence are mobilised and organised with the three analytic dimensions. To understand transitions from one system to another a multi-level perspective is described, where regimes are the meso-level. To understand regime changes interactions with two other levels are crucial (technological niches and socio-technical landscape). The paper ends with discussion and conclusions in Section 6.

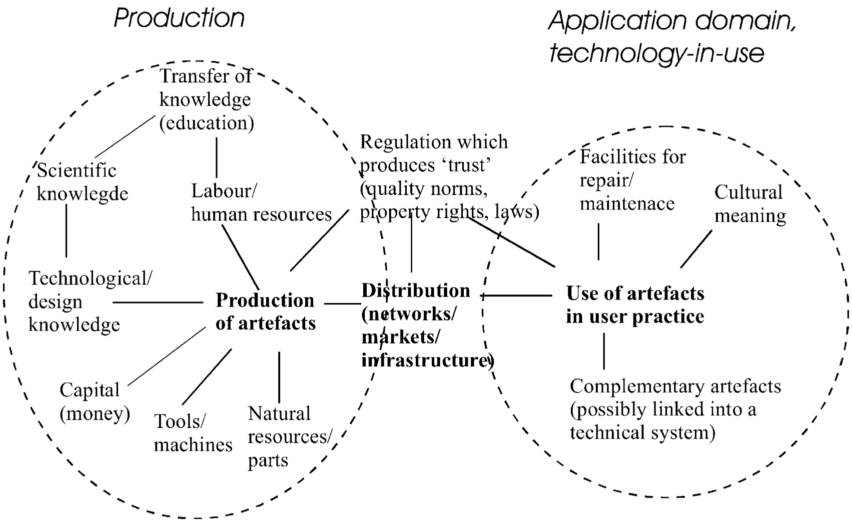

Fig. 1. The basic elements and resources of socio-technical systems.

2. From innovation systems to socio-technical systems

Existing innovation system approaches mainly focus on the production side where innovations emerge. To incorporate the user side explicitly in the analysis, the first contribution is to widen the analytic focus. I propose to look at socio-technical systems (ST-systems) which encompass production, diffusion and use of technology. I define ST-systems in a somewhat abstract, functional sense as the linkages between elements necessary to fulfil societal functions (e.g. transport, communication, nutrition). As technology is a crucial element in modern societies to fulfil those functions, it makes sense to distinguish the production, distribution and use of technologies as sub-functions. To fulfil these sub-functions, the necessary elements can be characterised as resources. ST-systems thus consist of artefacts, knowledge, capital, labour, cultural meaning, etc. (see Fig. 1).

The resources and fulfilment of sub-functions are not simply there. Socio-technical systems do not function autonomously, but are the outcome of the activities of human actors. Human actors are embedded in social groups which share certain characteristics (e.g. certain roles, responsibilities, norms, perceptions). In modern societies many specialised social groups are related to resources and sub-functions in ST-systems. Fig. 2 given a schematic representation.[1] This representation is similar to the social systems framework (Van de Ven and Garud, 1989; Van de Ven, 1993) and the innovation community perspective (Lynn et al., 1996; Reddy et al., 1991). It takes the inter-organisational community or field as the unit of analysis, and focuses on the social infrastructure necessary to develop, commercialise and use innovations. This perspective is wider than the focus on industry structures, commonly defined as a the set of firms producing similar or substitute products (Porter, 1980). Although firms and industries are important actors, other groups are also relevant, e.g. users, societal groups, public authorities, research institutes.

These social groups have relative autonomy. Each social group has its distinctive features. Members share particular perceptions, problem-agendas, norms, preferences, etc. They share a particular language ('jargon'), tell similar stories of their past and future, meet each other at particular fora, often read the same journals etc. In short, there is coordination *within* groups. Below I will use institutions and

[1] Fig. 2 can be made more complex by zooming in on actors *within* groups and linkages *between* groups. Then we also find professional societies, trade associations, distributors, various forms of industry consortia and university–industry relationships, consulting companies, semi-public government agencies, private research institutes, standard-setting bodies.

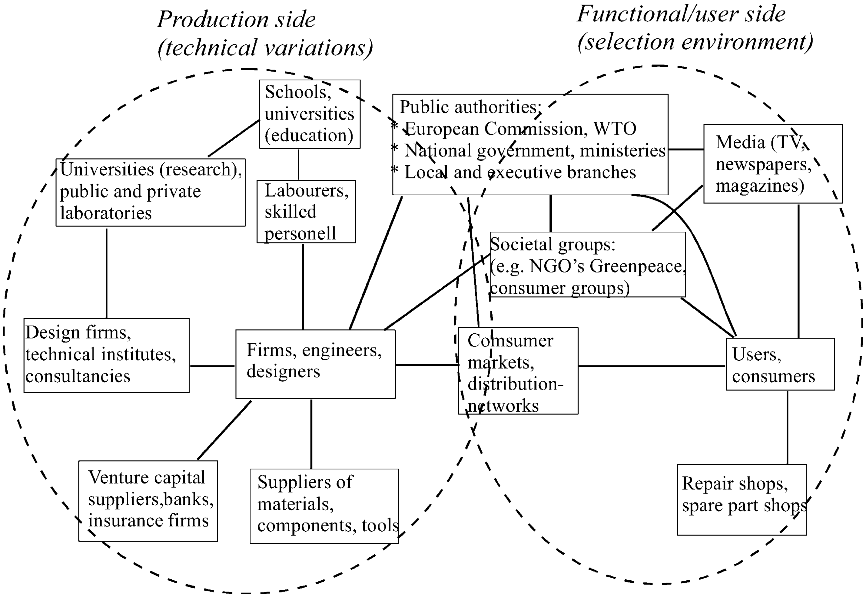

Fig. 2. Social groups which carry and reproduce ST-systems.

regimes to understand this intra-group coordination. But different groups also interact with each other, and form networks with mutual dependencies. Although groups have their own characteristics, they are also interdependent. Stankiewicz (1992) proposed the term 'interpenetration' to characterise groups, which overlap in some manner without loosing their autonomy and identity. Because of the interdependence activities of social groups are aligned to each other. This means there is also inter-group coordination. Below I will propose the concept of socio-technical regimes, to conceptualise this *meta-coordination*.

The relationship between sub-functions and resources on the one hand and social groups on the other hand is inherently dynamic. The configuration of social groups is the outcome of historical differentiation processes. Over time, social groups have specialised and differentiated, leading to more fine-grained social networks. The chains of social groups have lengthened over time (Elias, 1982). In the Middle Ages production and consumption were situated closely together. Knowledge, capital and labour were often located in the same producer (e.g. a blacksmith). In the last two centuries production and consumption have increasingly grown apart, because of efficient, low-cost transportation systems and because of mass-production methods (Beniger, 1986). The lengthening of networks led to an increase in social groups. Distribution involved an increasing number of social groups (e.g. merchants, wholesalers, retailers, chain stores). Techno-scientific knowledge has become more distributed over a widening range of actors (universities, laboratories, consultancies, R&D units in firms). The production of cultural and symbolic meanings involves an increasing range of mass media (newspapers, magazines, radio, TV, internet), especially in the 20th century. This dynamic of specialisation and differentiation means that it is not possible to define boundaries of social networks once and for all. Relationships between social groups shift over time and new groups emerge. In the electricity sector, for instance, liberalisation gave rise to electricity traders at spot markets as an entirely new group. This example also points to another point, namely that the precise configuration of social groups differs between sectors. The social network in transport systems looks and functions differently than in electricity systems. This means that boundary definition is more an empirical issue than a theoretical one.

In modern western societies production and use have increasingly differentiated into separate clusters. This has been accompanied by a similar differentiation in the social sciences. Evolutionary economics, business studies and innovation studies tend to focus mainly on the production-side and the *creation* of knowledge and innovation (e.g. learning within firms, organisational routines, knowledge management), while the user side has received less attention. Recently, there has been somewhat more attention in innovation studies for the co-evolution of technologies and markets (Green, 1992; Coombs et al., 2001). But in many studies, markets and users are simply assumed to be 'out there'. Another critique is that the selection environment is wider than users and markets. Policies and institutions also play a role, as well as infrastructures, cultural discourse or maintenance networks. Although Nelson (1994, 1995) has done some work on such wider co-evolution processes, the topic is under-exposed in evolutionary economics and innovation studies.

On the other hand, cultural studies and domestication studies focus more on the user side. They argue that consumption is more than simple adoption or buying, especially with regard to radically new technologies. Cultural appropriation of technologies is part of consumption (e.g. Du Gay et al., 1997; Van Dijck, 1998). Users also have to integrate new technologies in their practices, organisations and routines, something which involves learning, adjustments. New technologies have to be 'tamed' to fit in concrete routines and application contexts (including existing artifacts). Such domestication involves symbolic work, practical work, in which users integrate the artifact in their user practices, and cognitive work, which includes learning about the artifact (Lie and Sørensen, 1996). Domestication studies open up the 'black box' of adoption. Adoption is no passive act, but requires adaptations and innovations in the user context. David Nye (1990), for instance, beautifully described how the gradual integration of electricity in the factory, urban transportation, homes, and rural areas was accompanied by social and political struggles, uncertainty, learning processes and wider transformations. A disadvantage of user-focused approaches is that the *development* of technology disappears from view. Technology becomes a black box.

The advantage of looking explicitly at socio-technical systems is that the co-evolution of technology and society, of form and function becomes the focus of attention. Dynamics in ST-systems involve a dynamic

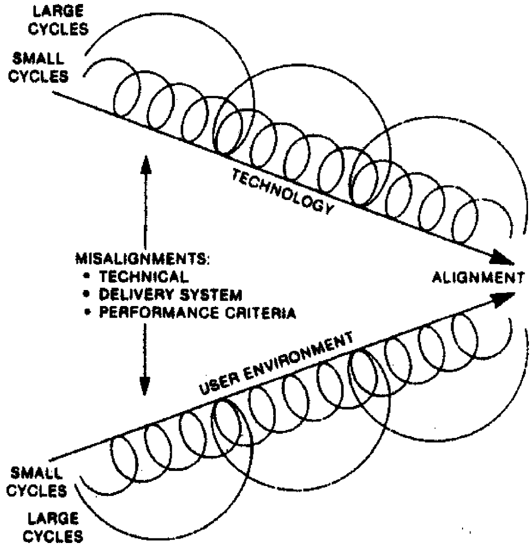

Fig. 3. Co-evolution of technology and user environment (Leonard-Barton, 1988, p. 251).

process of mutual adaptations and feedbacks between technology and user environment (Fig. 3). A focus on ST-system may form a bridge between separate bodies of literature.

Above I distinguished ST-systems on the one hand and human actors and the social groups on the other hand. But human actors are not entirely free to act as they want. Their perceptions and activities are coordinated (but not determined) by institutions and rules (this will be elaborated in Section 3). I can now make a second contribution to innovation studies, by suggestion an analytic distinction between ST-system, actors and institutions/rules, which guide actors (see Fig. 4).

Between the three dimensions, there are six kinds of interaction.

1. Actors reproduce the elements and linkages in ST-systems in their activities. This point has been made and empirically illustrated in approaches in sociology of technology, e.g. actor-network theory (see Latour, 1987, 1991, 1992; Callon, 1991), social construction of technology (see e.g. Pinch and Bijker, 1987; Kline and Pinch, 1996; Bijker, 1995) or large-technical systems theory (see Hughes, 1983, 1987; Mayntz and Hughes, 1988; La Porte, 1991; Summerton, 1994).
2. Because of their emphasis on product champions, 'heterogeneous engineers' (Law, 1987), 'system

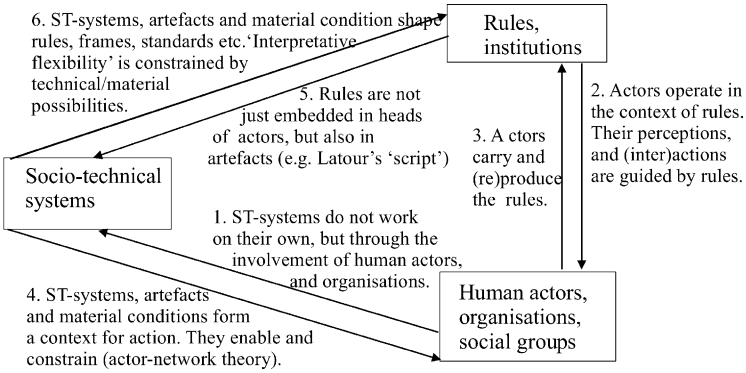

Fig. 4. Three interrelated analytic dimensions.

builders' (Hughes, 1987) these approaches sometimes tend towards voluntarism, with strong heroes shaping the world at will. To counter these tendencies attention also needs to be paid to existing rules, regimes and institutions which provide constraining and enabling contexts for actors (individual human beings, organisations, groups). Perceptions and (inter)actions of actors and organisations are guided by these rules ('structuration').

3. On the other hand, actors carry and (re)produce the rules in their activities.
4. While this 'duality of structure' has been well conceptualised in sociology, this discipline almost entirely neglects the material nature of modern societies. Technology studies, in particular actor-network theory, has criticised traditional sociology on this point. Human beings in modern societies do not live in a biotope, but in a technotope. We are surrounded by technologies and material contexts, ranging from buildings, roads, elevators, appliances, etc. These technologies are not only neutral instruments, but also shape our perceptions, behavioural patterns and activities. Socio-technical systems thus form a structuring context for human action. The difference between baboons and human beings is not just that the latter have more rules which structure social interactions, but also that they interact in a huge technical context (Strum and Latour, 1999).
5. Another insight from technology studies is that rules are not just shared in social groups and carried inside actors' heads, but can also be embedded in artefacts and practices. Adding insights from science and technology studies to evolutionary economics, Rip and Kemp (1998), therefore, re-defined the concept of 'technological regime' as:

A technological regime is the rule-set or grammar embedded in a complex of engineering practices, production process technologies, product characteristics, skills and procedures, ways of handling relevant artefacts and persons, ways of defining problems; all of them embedded in institutions and infrastructures

(Rip and Kemp, 1998, p. 340).

Similar notions of how rules are embedded in artefacts can be found in the philoshophy of technology, where Winner (1980) advanced the notion that technologies could have political effects built into them. Winner described the example of Moses' bridges on Long Island, New York, which were built very low, so that only automobiles could pass under them, not buses. "Poor people and blacks, who normally used public transit, were kept off the roads because the twelve-foot buses could not get through the overpasses. One consequence was to limit access to Jones Beach, Moses's widely acclaimed public park" (Winner, 1980: 28). Actor-network theorists such Akrich (1992) and Latour (1992) introduced the notion of the 'script' of an artefact to capture how technological objects enable or constrain human relations as well as relationships between people and things. 'Like a film script, technical objects define a framework of action together with the actors and space in which they are supposed to act' (Akrich, 1992, p. 208).

6. Technologies have a certain ‘hardness’ or obdurancy, which has to do with their material nature, but also with economic aspects (e.g. sunk costs). Because of this hardness, technologies and material arrangements may be harder to change than rules or laws. They may even give social relationships more durability (Latour, 1991). This hardness also implies that artefacts cannot entirely be shaped at will. Although I am sympathetic about social construction of technology (Pinch and Bijker, 1987; Bijker, 1995), there are limits to the interpretative flexibility of artefacts. Technical possibilities and scientific laws constrain the degree to which interpretations can be made. Next to social shaping, there is also technical shaping (Vincenti, 1995; Molina, 1999).

The three dimensions in Fig. 4 are always interrelated in practice. For analytical purposes, however, it is useful to distinguish these three dimensions, so that interactions can be investigated. This will be done in the following sections.

3. Coordination of activities through institutions and rules

In this section, I will open up the black box of institutions. To avoid confusion between institutions and (public) organisations, I propose the general sociological concept of ‘rules’ instead. Although one can quarrel about terms and exact definitions, it is more important to look at the general phenomena they aim to describe, i.e. coordination and structuration of activities. With regard to that aim, rules are similar to institutions.

3.1. Different kinds of coordination: cognitive, normative and regulative rules

The aim in this article is not to give an exhaustive overview of all possible rules and the different disciplines they come from. It is useful, however, to give an analytic grouping of different kinds of rules. Scott (1995) distinguishes three dimensions or ‘pillars’: regulative, normative and cognitive rules. The *regulative* dimension refers to explicit, formal rules, which constrain behaviour and regulate interactions, e.g. government regulations which structure the economic process. It is about rewards and punishments backed up with sanctions (e.g. police, courts). Institutional economists tend to highlight these formal and regulative rules (e.g. Hodgson, 1998). North (1990), for instance, highlights rules which structure economic processes at the national level (e.g. property rights, contracts, patent laws, tax structures, trade laws, legal systems). *Normative* rules are often highlighted by traditional sociologists (e.g. Durkheim, 1949; Parsons, 1937). These rules confer values, norms, role expectations, duties, rights, responsibilities. Sociologists argue that such rules are internalised through socialisation processes. *Cognitive* rules constitute the nature of reality and the frames through which meaning or sense is made. Symbols (words, concepts, myths, signs, gestures) have their effect by shaping the meanings we attribute to objects and activities. Social and cognitive psychologists have focused on the limited cognitive capacities of human beings and how individuals use schemas, frames, cognitive frameworks or belief systems to select and process information (e.g. Simon, 1957). Evolutionary economists and sociologists of technology have highlighted cognitive routines, search heuristics, exemplars, technological paradigms and technological frames of engineers in firms and technical communities (e.g. Nelson and Winter, 1982; Dosi, 1982; Bijker, 1995). Table 1 briefly indicates the differences between these types of rules.

3.2. Different rules and regimes for different social groups

Rules do not exist as single autonomous entities. Instead, they are linked together and organised into rule *systems*. Rule systems may be purely private rule or ‘personality systems’ or they may be collectively shared systems. The latter case refers to social rule systems. Social rule systems, which structure and regulate social transactions and which are backed by social sanctions and networks of control, are referred to as rule regimes (Burns and Flam, 1987, p. 13). I understand *regimes* as semi-coherent sets of rules, which are linked together. It is difficult to change one rule, without altering others. The alignment between rules gives a regime stability, and ‘strength’ to coordinate activities.

Table 1
Varying emphasis: three kinds of rules/institutions (Scott, 1995, pp. 35, 52)

	Regulative	Normative	Cognitive
Examples	Formal rules, laws, sanctions, incentive structures, reward and cost structures, governance systems, power systems, protocols, standards, procedures	Values, norms, role expectations, authority systems, duty, codes of conduct	Priorities, problem agendas, beliefs, bodies of knowledge (paradigms), models of reality, categories, classifications, jargon/language, search heuristics
Basis of compliance	Expedience	Social obligation	Taken for granted
Mechanisms	Coercive (force, punishments)	Normative pressure (social sanctions such as 'shaming')	Mimetic, learning, imitation
Logic	Instrumentality (creating stability, 'rules of the game')	Appropriateness, becoming part of the group ('how we do things')	Orthodoxy (shared ideas, concepts)
Basis of legitimacy	Legally sanctioned	Morally governed	Culturally supported, conceptually correct

In Section 2, different social groups were distinguished, with their own distinctive features. Actors within these groups share a set of rules or regime. As the different groups share different rules, we may distinguish different regimes, e.g. technological or design regimes, policy regimes, science regimes, financial regimes and societal or user regimes. Actors in these different communities tend to read particular professional journals, meet at specialised conferences, have professional associations and lobby clubs, share aims, values and problem agendas etc.[2] If we cross the different social groups with the different kinds of rules, we get an analytical tool to describe the different regimes. Table 2 presents a first attempt to use this tool, trying to bring together and position different rules and institutions from different literatures (e.g. sociology of technology, evolutionary economics, innovation studies, institutional economics, business studies, cultural studies).

3.3. *Meta-coordination through socio-technical regimes*

Table 2 shows that regimes exist of interrelated rules. Rules are not just linked within regimes, but also *between* regimes. The search heuristics of engineers are usually linked to user representations formulated by marketing departments. In stable markets, these user representations are aligned with user preferences. Search heuristics are also linked to product specifications, which in turn are linked to formal regulations (e.g. emission standards).

This means there are linkages between regimes. This helps to explain the alignment of activities between different groups. To understand this meta-coordination I propose the concept of *socio-technical regimes*. ST-regimes can be understood as the 'deep-structure' or grammar of ST-systems, and are carried by the social groups. ST-regimes do not encompass the entirety of other regimes, but only refer to those rules, which are aligned to each other (see Fig. 5). It indicates that different regimes have relative autonomy on the one hand, but are interdependent on the other hand.

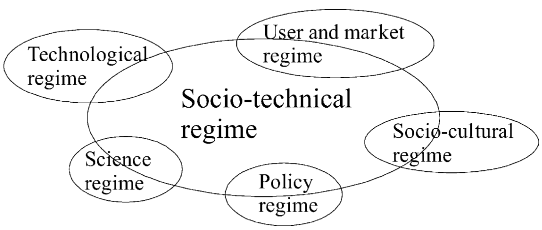

Fig. 5. Meta-coordination through socio-technical regimes.

[2] Societal or user regimes are somewhat more problematic in this respect, because such institutional and organizational structures are largely lacking, and there is less coordination of the individual members.

Table 2
Examples of rules in different regimes

	Formal/regulative	Normative	Cognitive
Technological and product regimes (research, development production)	Technical standards, product specifications (e.g. emissions, weight), functional requirements (articulated by customers or marketing departments), accounting rules to establish profitability for R&D projects (Christensen, 1997), expected capital return rate for investments, R&D subsidies.	Companies own sense of itself (what company are we? what business are we in?), authority structures in technical communities or firms, testing procedures.	Search heuristics, routines, exemplars) (Dosi, 1982; Nelson and Winter, 1982), guiding principles (Elzen et al., 1990), expectations (Van Lente, 1993; Van Lente and Rip, 1998), technological guideposts (Sahal, 1985), technical problem agenda, presumptive anomalies (Constant, 1980), problem solving strategies, technical recipes, 'user representations' (Akrich, 1995), interpretative flexibility and technological frame (Bijker, 1995), classifications (Bowker and Star, 2000).
Science regimes	Formal research programmes (in research groups, governments), professional boundaries, rules for government subsidies.	Review procedures for publication, norms for citation, academic values and norms (Merton, 1973).	Paradigms (Kuhn, 1962), exemplars, criteria and methods of knowledge production.
Policy regimes	Administrative regulations and procedures which structure the legislative process, formal regulations of technology (e.g. safety standards, emission norms), subsidy programs, procurement programs.	Policy goals, interaction patterns between industry and government (e.g. corporatism), institutional commitment to existing systems (Walker, 2000), role perceptions of government.	Ideas about the effectiveness of instruments, guiding principles (e.g. liberalisation), problem-agendas.
Socio-cultural regimes (societal groups, media)	Rules which structure the spread of information production of cultural symbols (e.g. media laws).	Cultural values in society or sectors, ways in which users interact with firms (Lundvall, 1988).	Symbolic meanings of technologies, ideas about impacts, cultural categories.
Users, markets and distribution networks	Construction of markets through laws and rules (Callon, 1998, 1999; Green, 1992; Spar, 2001); property rights, product quality laws, liability rules, market subsidies, tax credits to users, competition rules, safety requirements.	Interlocking role relationships between users and firms, mutual perceptions and expectations (White, 1981, 1988; Swedberg, 1994).	User practices, user preferences, user competencies, interpretation of functionalities of technologies, beliefs about the efficiency of (free)markets, perceptions of what 'the market' wants (i.e. selection criteria, user preferences).

4. Dynamic interactions between systems, actors and rule-regimes

Having described the three analytical dimensions (systems, actors, rules), this section investigates dynamic interactions between them.

4.1. Dynamic interactions between rule-regimes and actors

There are two fundamentally different conceptions of the activities of human actors. In the first, social actors are viewed as the essential sources and forces of social changes. The individual, the strong personality as exemplified by Schumpeter's entrepreneur or Hughes' system builder, enjoys an extensive freedom to act. In the second conception social actors are faceless automata following iron rules or given roles/functions in social structures which they cannot basically change. While the first view emphasises agency, the second highlights the effects of structures.

In recent decades, conceptual approaches have been developed which attempt to solve the structure-agency dilemma (e.g. Giddens, 1984; Bourdieu, 1977; Burns and Flam, 1987). In these approaches, actors are seen as embedded in wider structures, which configure their preferences, aims, strategies. Despite these structuring effects, the approaches leave much room to actors and agency, i.e. conscious and strategic actions. Giddens, for instance, talks of the 'duality of structure', where structures are both the product and medium of action. Bourdieu coined terms such as 'habitus' and 'field' to conceptualise similar notions. And Burns and Flam developed a 'social rule system theory' to understand dynamic relationships between actors and structure. In all these approaches 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 these systems. Another important point is that structures not only *constrain* but also *enable* action, i.e. make it possible by providing coordination and stability.

I will briefly discuss Burns and Flam (1987), because of their explicit attention and schematisation of interactions between actors and social rule systems. As members of social groups, actors share a set of rules or regime, which guide their actions. These rules are the outcome of earlier (inter)actions. Social actors knowledgeably and actively use, interpret and implement rule systems. They also creatively reform and transform them. Rules are implemented and (re)produced in social activities which take place in concrete interaction settings (local practices). Through implementing the shared rule systems, the members of collectivities generate patterns of activity, which are similar across different local practice. While there is similarity to some degree, there is also variety between group members. Members also have private rule systems, somewhat different strategies, different resource positions, etc. As a result, there may be variation in local practices, within a shared social rule system. The strategies, interests, preferences, etc. are not fixed, but change over time as a result of social action. Actors act and interact with each other in concrete settings or local practices. For instance, firms make strategic investment decisions, public authorities make new policy plans and regulations, etc. The aim of these actions is usually to improve their situation and control of resources (e.g. earning money, market position, strategic position), i.e. it is motivated by self-interest. Enactment of social rules in (inter)action usually has effects on the physical, institutional and cultural conditions of action, some of which will be unintended. Some effects will directly influence actors, e.g. their resource positions, market shares, money. These direct effects are called '*actor structuring*'. This may involve individual learning when specific actors (e.g. firms) evaluate their actions, learn, and adjust their strategies, aims, preferences, etc. Other effects influence the shared rule system (e.g. perceptions of who the users are, what they want, which technical recipes work best) and are called '*social learning*', because they take place at the level of the entire group. This takes place through imitation[3] (firms imitate routines from successful firms) or through the exchange of experiences, e.g. articulation of problem agendas and best practices at conferences, through specialised journal or professional societies and branch organisations. Through the effects of social interaction, social rule systems as well as social agents are maintained and changed. Fig. 6 gives an impression of these basic dynamics. Fig. 6 also includes exogenous factors which conditionally structure actors, social action and system development, but which are not influenced by them (Burns and Flam, 1987, p. 3). These exogenous factors may change over time and impact on social rule systems causing internal restructuring.

Fig. 6 includes two feedback loops, an upper one (social learning) and a bottom one (actor structuring).

[3] See also Nelson and Winter (1982), p. 135, according to whom "imitation is an important mechanism by which routines come to organize a larger fraction of the total activity of the system", thus playing a role in the emergence of technological regimes.

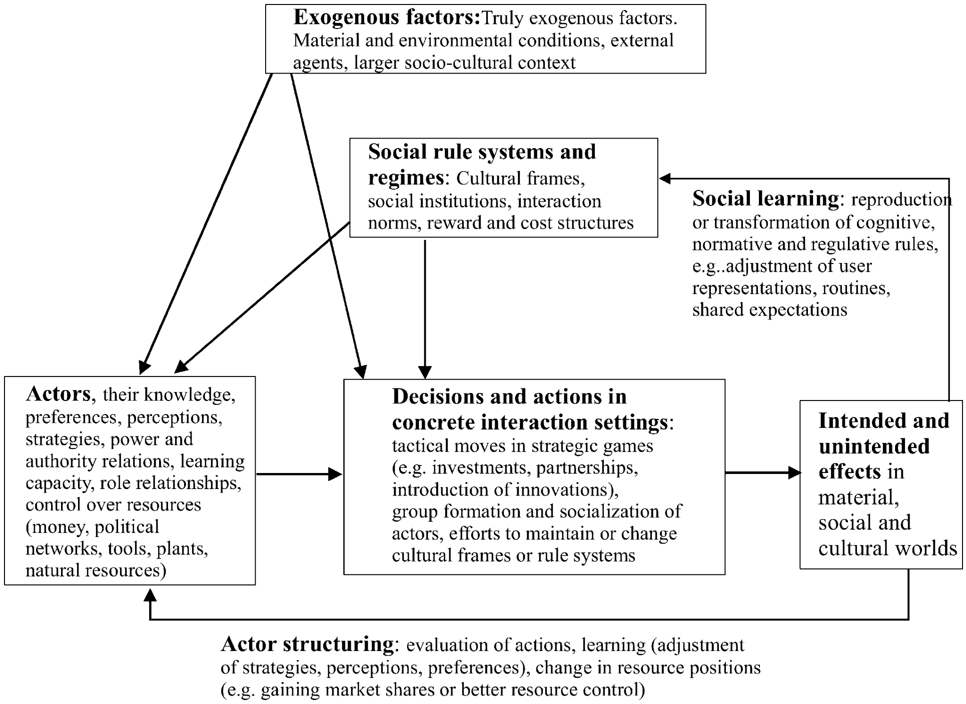

Fig. 6. Actor-rule system dynamics (adapted from Burns and Flam, 1987, p. 4).

The upper loop represents sociological and institutional dynamics, and can best be applied on longer time-scales (years, decades). For example, government policies often take years before they have substantial effects at the level of systems. Likewise the articulation of new user preferences or new technical search heuristics may take years, because it occurs in small incremental steps, and often involves experiments and set-backs. Examples are the public acceptance of walkmans (Du Gay et al., 1997) or the development of wind turbines (Garud and Karnøe, 2003). The bottom loop represents interactions between actors, affecting their positions and relationships. This includes dynamics which are emphasised in business studies and industrial economics, e.g. strategic games in markets, power struggles, strategic coalitions, innovation race. The time-scale of this loop is usually shorter (e.g. months, years). Fig. 6 thus aims to combine and position sociological and economic analyses. The aim is not to argue for the ultimate primacy of sociology, but to develop a dynamic framework, where economic activities and processes are on the one hand structured, but on the other hand influence and transform the sociological structures in which they are embedded. For short-term analyses, the sociological structures may be assumed relatively constant, providing a frame for R&D strategies, strategic games, etc. For longer-term analyses (e.g. changes from one socio-technical system to another) the sociological loop also needs to be included, and attention should be paid to social learning and institutional change.

4.2. Dynamic interactions between actors and systems: making moves in games

On the one hand, ST-systems are maintained and changed by activities of actors, on the other hand, they form a context for actions. We can understand these actions as moves in a game, of which the rules somewhat alter while the game is being played. Economic processes are embedded in sociological processes, but are not entirely determined by them. Within rules and regimes there is plenty of room for intelligent interpretation, strategic manoeuvring, etc. Institutional economists coined the notion of 'rules of the game'. Rules and regimes constitute a game, which is played out by actors, firms, public authorities, users, scientists, suppliers, etc. The different social groups each have their own perceptions, preferences, aims, strategies, resources, etc. Actors within these groups act to achieve their aims, increase their resource positions, etc. Their actions and interactions can be seen as an ongoing game in which they react to each other. The feedback loops in Fig. 6 indicate that there are multiple development rounds. In each round actors make 'moves', i.e. they do something, e.g. make investment decisions about R&D directions, introduce new technologies in the market, develop new regulations, propose new scientific hypotheses. These actions maintain or change aspects of ST-systems. The dynamic is game-like because actors react to each other's moves. These games may be *within* groups, e.g. firms who play strategic games between each other to gain competitive advantage. There may also be games *between* groups, e.g. between an industry and public authorities. For instance, public authorities may want to stimulate the environmental performance of cars, but they do not know exactly which regulations and emission standards are feasible. The car industry wants to prevent very strict regulations, but also show public authorities their good will ('with this new clean car, we are doing the best we can'). If one company opts for a strategy to introduce an even cleaner car, this changes the game, because it allows public authorities to introduce stricter rules to force other companies to do the same. With the stricter emission rules, the game has changed (somewhat). The added value of this conceptualisation (compared to institutional economists) is that the 'rules of the game' are not fixed, but may change during the game, over successive development rounds. It also shows how ST-systems change because of activities and (strategic) games between actors. The notion of 'playing games' also highlights that social (inter)action in the context of regimes is not necessarily harmonious. Different actors do not have equal power or strength. They have unequal resources (e.g. money, knowledge, tools) and opportunities to realise their purposes and interest, and influence social rules. The framework leaves room for conflict and power struggles. After all, there is something at stake in the games.

4.3. Co-evolution in ST-systems

Each of the social groups has internal dynamics, its own games in the context of problem agendas, search heuristics, repertoires, etc. But because social groups interpenetrate there are also games between groups (see the example of car industry and regulators). The ongoing games within and between groups lead to changes in ST-systems, because the moves actors make have effects. Moves may lead to improvements of existing technologies or introduction of new technologies. In reaction to new technologies, policy makers may develop new rules to regulate it, and users may develop new behaviour. The consequence of these multiple games is that elements of ST-systems co-evolve. There is not just one kind of dynamic in ST-systems, but multiple dynamics which interact with each other. Co-evolution is increasingly recognised as an important issue, e.g. in evolutionary economics (e.g. Nelson, 1994, 1995), long-wave theory (Freeman and Louça, 2001), and innovation studies. It has always been an important theme in science and technology studies, with its emphasis on seamless webs, emerging linkages between heterogeneous elements and co-construction (actor-network theory, social construction of technology, large-technical systems theory). Aspects of co-evolution have been dealt with in different literatures, e.g.:

- Co-evolution between technology and users (Coombs et al., 2001; Lundvall, 1988; Leonard-Barton, 1988; Lie and Sørensen, 1996; Oudshoorn and Pinch, 2003).
- Co-evolution between technology, industry structure and policy institutions (Nelson, 1994, 1995; Van de Ven and Garud, 1994; Rosenkopf and Tushman, 1994; Lynn et al., 1996; Leydesdorff and Etzkowitz, 1998).
- Co-evolution of science, technology and the market (Callon, 1991; Stankiewicz, 1992).
- Co-evolution of science and technology (Kline and Rosenberg, 1986; Layton, 1971, 1979).
- Co-evolution of technology and culture (Du Gay et al., 1997; Van Dijck, 1998).
- Co-evolution of technology and society (Rip and Kemp, 1998; Freeman and Soete, 1997).

Although co-evolution has been studied with regard to two or three aspects, there are few literatures which look at co-evolution in entire ST-systems. A broader study of co-evolution is lacking. Below I will suggest the co-evolution of five different regimes as a first step in the direction of a wider co-evolution study.

5. Stability and change: a multi-level perspective on transitions

The systems of innovation literature has not paid much attention to the transition from one system to another. To address this topic, I will first discuss the stability of existing ST-systems. Then I will describe how radical innovations emerge. The section ends with a multi-level perspective on the transformation of ST-systems.

5.1. *Understanding stability of existing ST-systems: path-dependence and lock-in*

Socio-technical systems, rules and social groups provide stability through different mechanisms. Following the seminal articles by David (1985) and Arthur (1988) other authors have used the notions of path-dependence and lock-in to analyse the stability at the level of existing systems (Unruh, 2000; Jacobsson and Johnson, 2000; Walker, 2000; Araujo and Harrison, 2002). The three interrelated concepts of ST-systems, rules and social groups can be used to group their insights and highlight different aspects of stability.

First, *rules and regimes* provide stability by guiding perceptions and actions. Because rules tend to be reproduced, they were characterised above as the deep structure or grammar of ST-systems. In a similar fashion, Nelson and Winter (1982), p. 134, referred to routines as 'genes' of technological development. And David (1994) referred to institutions as the 'carriers of history'. I distinguished three kinds of rules which stabilise ST-systems in different ways.

- *Cognitive rules*: cognitive routines make engineers and designers look in particular directions and not in others (Nelson and Winter, 1982; Dosi, 1982). This can make them 'blind' to developments outside their focus. Core capabilities can turn into core rigidities (Leonard-Barton, 1995). Competencies, skills, knowledge also represent a kind of 'cognitive capital' with sunk investments. It takes much time to acquire new knowledge and build up competencies. It is often difficult for established firms and organisations to develop or switch to competence destroying breakthroughs (Tushman and Anderson, 1986; Christensen, 1997). Learning is cumulative in the sense that it builds upon existing knowledge and refines it. Hence, learning is a major contributor to path dependence.
  Important cognitive rules are shared belief systems and expectations, which orient perceptions of the future and hence steer actions in the present. As long as actors (e.g. firms) expect that certain problems can be solved within the existing regime, they will not invest in radical innovations and continue along existing paths and 'technical trajectories' (Dosi, 1982). Other important cognitive rules are perceptions of user preferences (Akrich, 1995). As long as firms think that they meet user preferences well, they will continue to produce similar products (Christensen, 1997).
- *Normative rules*: social and organisational networks are stabilised by mutual role perceptions and expectations of proper behaviour. In some relationships it is not seen as 'proper' to raise certain issues. Verheul (2002) found that metal-plating businesses did not raise environmental issues in meetings with customers, because they felt this was inappropriate. They thought customers were more interested in consistent product quality than in environmental performance.
- *Regulative and formal rules*: established systems may be stabilised by legally binding contracts. Walker (2000) described how a particular nuclear reprocessing plant was locked in because of contracts between British Nuclear Fuels and its foreign customers. Other stabilising formal rules may be technical standards, or rules for government subsidies which favour existing technologies.
- A fourth type of stability is the alignment between rules. It is difficult to change one rule, without altering others.

Second, *actors and organisations* are embedded in interdependent networks and mutual dependencies which contribute to stability. Once networks have formed they represent a kind of ‘organisational capital’, i.e. knowing who to call upon (trust). In organisation studies it has been found that organisations (e.g. firms) are resistant to major changes, because they develop “webs of interdependent relationships with buyers, suppliers, and financial backers (...) and patterns of culture, norms and ideology” (Tushman and Romanelli, 1985, p. 177). The stability of organisations stems from ‘organisational deep structures’, i.e. a system of interrelated organisational parts maintained by mutual dependencies among the parts and “cognitive frameworks which shape human awareness, interpretation or reality, and consideration of actions” (Gersick, 1991, p. 18). Another factor are organisational commitments and vested interests of existing organisations in the continuation of systems (Walker, 2000). “The large mass of a technological system arises especially from the organisations and people committed by various interests to the system. Manufacturing corporations, public and private utilities, industrial and government research laboratories, investment and banking houses, sections of technical and industrial societies, departments in educational institutions and regulatory bodies add greatly to the momentum of modern electric light and power systems” (Hughes, 1987, pp. 76–77). Powerful incumbent actors may try to suppress innovations through market control or political lobbying. Industries may even create special organisations, which are political forces to lobby on their behalf, e.g. professional or industry associations, branch organisations (Unruh, 2000).

Third, *socio-technical systems*, in particular the artefacts and material networks, have a certain ‘hardness’, which makes them difficult to change. Once certain material structures or technical systems, such as nuclear re-processing plants, have been created, they are not easily abandoned, and almost acquire a logic of their own (Walker, 2000). Complementarities between components and sub-systems are an important source of inertia in complex technologies and systems (Rycroft and Kash, 2002; Arthur, 1988). These components and sub-systems depend on each other for their functioning. This system interdependence is a powerful obstacle for the emergence and incorporation of radical innovations. The stability is often formalised in compatibility standards. Material artefacts are also stabilised because they are embedded in society; hence the term socio-technical systems. People adapt their lifestyles to artifacts, new infrastructures are created, industrial supply chains emerge, making it part of the economic system dependent on the artifact. Thus, technological momentum emerges (Hughes, 1994). Because of all these linkages, it becomes nearly unthinkable for the technology to change in any substantial fashion. A ‘reversal’ occurs as the technology shifts from flexibility to ‘dynamic rigidity’ (Staudenmaier, 1989). A particular aspect of stability are network externalities (Arthur, 1988). This means that the more a technology is used by other users, the larger the availability and variety of (related) products that become available and are adapted to the product use. Furthermore, the functionality of network technologies (such as telephones, internet, etc.) increases as more people are connected. Of course, economic considerations also are important to explain the stability of socio-technical systems. There may be sunk investments in infrastructure, production lines, skills. As shifting to a new technological path would destroy these sunk investment, firms tend to stick to established technologies as long as possible. And there are often economies of scale, which allow the price per unit to go down and hence improve competitiveness (Arthur, 1988). Learning by doing (Arrow, 1962) and learning by using also improve competitiveness. The more a technology is produced and used, the more is learned about it, and the more it is improved.

The different sources of path dependence are a powerful incentive for incremental innovations in socio-technical systems, leading to particular paths or trajectories. Within technological regimes (paradigms) this leads to technological trajectories (Dosi, 1982). In a recent contribution to long-wave theories, Freeman and Louça (2001) focused on interactions between five sub-systems: science, technology, economy, politics and culture, each with their own development line. They argue that: “It is essential to study both the relatively independent development of each stream of history and their interdependencies, their loss of integration, and their reintegration” (p. 127). This means that there are not just trajectories in technological regimes, but also in other regimes. These trajectories are the outcome of an accumulation of steps in particular path dependent directions (see Fig. 7). To understand dynamics in ST-systems

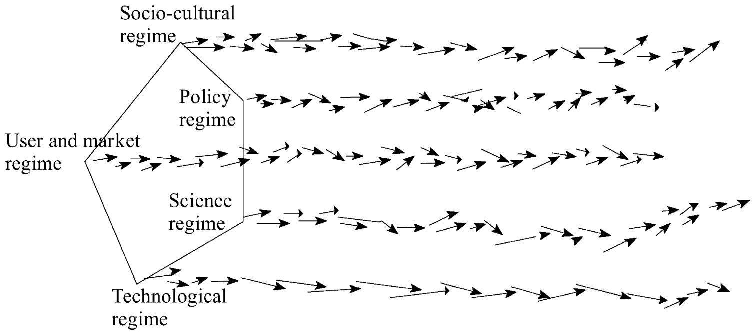

Fig. 7. Alignment of trajectories in different regimes.

we should look at the co-evolution of multiple trajectories.

5.2. The emergence of radical innovations in niches

Because of path dependence and stability it is difficult to create radical innovations within ST-systems. So, how do radical innovations emerge? Some scholars in sociology of technology and evolutionary economics have highlighted the importance of *niches* as the locus of radical innovations. As the performance of radical novelties is initially low, they emerge in 'protected spaces' to shield them from mainstream market selection. Protection is often provided in terms of subsidies, by public authorities or as strategic investments within companies ('skunk works'). Niches act as 'incubation rooms' for radical novelties. Niches may have the form of small market niches with specific (high-performance) selection criteria (Levinthal, 1998) or the form of technological niches. The latter are often played out as experimental projects, involving heterogeneous actors (e.g. users, producers, public authorities). Some examples are experiments in the 1990s with electric vehicles in various European countries and cities (Rochelle, Rugen, Gothenborg, etc.) or experiments with solar cells in houses (Hoogma, 2000; Van Mierlo, 2002).

Niches are important, because they provide locations for learning processes, e.g. about technical specifications, user preferences, public policies, symbolic meanings. Niches are locations where it is possible to deviate from the rules in the existing regime. The emergence of new paths has been described as a 'process of mindful deviation' (Garud and Karnøe, 2001), and niches provide the locus for this process. This means that rules in technological niches are less articulated and clear-cut. There may be uncertainty about technical design rules and search heuristics, and niches provide space to learn about them. For instance, are nickel–cadmium batteries better in electric vehicles than lead acid batteries or not? How do users feel about different electric vehicles, e.g. with regard to maintenance or range? Are there adjustments in user behaviour such as better planning of trips to deal with limited-range issues? What kind of use would be best suited for a particular electric vehicle: a 'normal' sedan, a station car (to drive small distances to train stations), a second car in the household (e.g. for shopping or picking children up from school)? While niches deviate from regime-rules on some dimensions, they also tend to stick to existing rules on other dimensions. They may deviate on technical rules, but stay close to existing rules with regard to users and behaviour. Niches are more radical as they deviate on more rules. Niches also provide space to build the social networks which support innovations, e.g. supply chains, user–producer relationships. Actors are willing to support and invest in niches because they have certain expectations about possible futures. The internal niche processes (learning, network building and expectations) have been analysed and described under the heading of strategic niche management (Schot et al., 1994; Kemp et al., 1998, 2001; Hoogma, 2000; Hoogma et al., 2002).

The three analytic dimensions also apply to niches (rules, actors, system). The difference with socio-technical systems and regimes is the degree of stability (and the fact that niches often get some

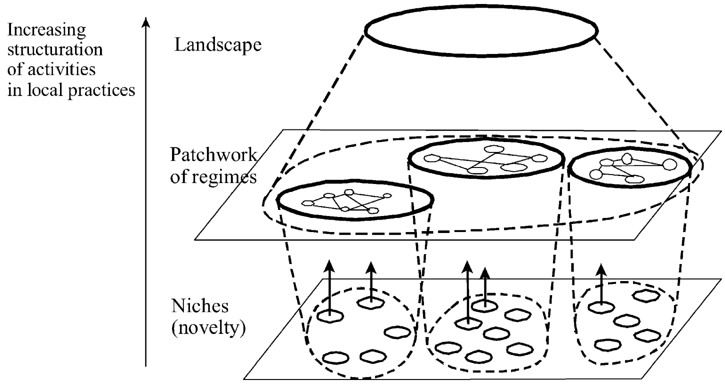

Fig. 8. Multiple levels as a nested hierarchy (Geels, 2002a).

form of protection). In niches not all rules have yet crystallised. There may be substantial uncertainty about the best design heuristics, user preferences, behavioural patterns, public policies, etc. There may also be uncertainty about the social network. The network of experimental projects is often contingent. Some actors participate in this project, but not in another. There are no clear role relationships, interlinked dependencies and normative rules. And the socio-technical configuration also tends to be in flux. Which components should be used in technical systems, how should the systems architecture be arranged? What arrangements should be made with regard to infrastructure, supplies of tools and components? In sum, actors in niches need to put in a lot of 'work' to uphold the niche, and work on the articulation of rules and social networks. As the rules are less clear, there is less structuration of activities. There is more space to go in different directions and try out variety. Rules and social networks may eventually stabilise as the outcome of successive learning processes. In regimes, on the other hand, rules have become stable and have more structuring effects. Fig. 8 represents this difference.

Fig. 8 also includes the concept of socio-technical landscape, which refers to aspects of the wider exogenous environment (to account for the 'exogenous factors' from Burns and Flam's rule system theory in Fig. 6). The metaphor 'landscape' is used because of the literal connotation of relative 'hardness' and to include the material aspect of society, e.g. the material and spatial arrangements of cities, factories, highways, and electricity infrastructures. *Sociotechnical landscapes* provide even stronger structuration of activities than regimes. This does not necessarily mean they have more effects than regimes, but refers to the relationship with action. Landscapes are beyond the direct influence of actors, and cannot be changed at will. Material environments, shared cultural beliefs, symbols and values are hard to deviate from. They form 'gradients' for action.

The work in niches is often geared to the problems of existing regimes (hence the arrows in Fig. 8). Niche-actors hope that the promising novelties are eventually used in the regime or even replace it. This is not easy, however, because the existing regime is stable in many ways (e.g. institutionally, organisationally, economically, culturally). Radical novelties may have a 'mis-match' with the existing regime (Freeman and Perez, 1988) and do not easily break through. Nevertheless, niches are crucial for system innovations, because they provide the seeds for change.

5.3. Tensions, mis-alignment and instability

To understand transitions from one system to another the notions of tensions and mis-alignment are useful. The different regimes have internal dynamics, which generate fluctuations and variations, (e.g. political cycles, business cycles, technological trajectories, cultural movements and hypes, lifecycles of industries). These fluctuations are usually dampened by the linkages with other regimes, thus providing co-ordination. At times, however, the fluctuations may result in mal-adjustments, lack of synchronicities and tensions (see also Freeman and Louça, 2001). When the activities of different social groups and the resulting trajectories go in different directions, this leads to 'mis-alignment' and instability of ST-systems. This means that both stability and change of ST-systems are the result of the actions and interactions between multiple social groups. The tensions and mis-matches of activities are mirrored in socio-technical regimes, in the form of tensions or mis-matches between certain rules, creating more space for interpretative flexibility for actors. For instance, goals in policy regimes may not be aligned with problem agendas and search heuristics in technological regimes. When changes in cultural values and user preferences are not picked up by marketing departments, the existing user representations may be at odds with real user preferences. Incentives for researchers (e.g. publication rules) may be at odds with societal problem agendas, meaning that research does not contribute to solving the problems.

5.4. A multi-level perspective on system innovations

The three levels introduced above can be used to understand system innovations. I will only briefly outline the multi-level framework, which has been described more elaborately elsewhere (Rip and Kemp, 1998; Kemp et al., 2001; Geels, 2002a, b). As long as ST-regimes are stable and aligned, radical novelties have few chances and remain stuck in particular niches. If tensions and mis-matches occur, however, in the activities of social groups and in ST-regimes, this creates 'windows of opportunity' for the breakthrough of radical novelties. There may be different reasons for such tensions and mis-alignment:

- Changes on the landscape level may put pressure on the regime and cause internal restructuring (Burns and Flam, 1987). Climate change, for instance, is currently putting pressure on energy and transport sectors, triggering changes in technical search heuristics and public policies. Broad cultural changes in values and ideologies, or change in political coalitions may also create pressure.
- Internal technical problems may also trigger actors (e.g. firms, engineers) to explore and invest more in new technical directions. Different terms have been proposed in the literature, e.g. 'bottlenecks' (Rosenberg, 1976), 'reverse salients' (Hughes, 1987), 'diminishing returns of existing technology' (Freeman and Perez, 1988), *expected* problems and 'presumptive anomalies' (Constant, 1980). It is not just the existence of technical problems, but the shared perception and placement on problem agendas which is important. Continuing problems can undermine the trust in existing technologies and alter expectations of new technologies.
- Negative externalities and effects on other systems (e.g. environmental impacts, health risks and concerns about safety) may lead to pressure on the regime. Actors inside the regime tend to downplay negative externalities. The externalities have to be picked up and problematised by 'outsiders', e.g. societal pressure groups (e.g. Greenpeace), outside engineering and scientific professionals, or outside firms (Van de Poel, 2000). To get negative externalities on the technical agenda of regime actors, there may be a need for consumer pressures and regulatory measures.
- Changing user preferences may lead to tensions when established technologies have difficulties to meet them. User preferences may change for many reasons, e.g. concern about negative externalities, wide cultural changes, changes in relative prices, policy measures such as taxes. User preferences may also change endogenously, as users interact with new technologies, and discover new functionalities.
- Strategic and competitive games between firms may open up the regime. New technologies are one way in which companies (or countries) try to get a competitive advantage. That is why they make strategic investments in R&D. Although most R&D goes towards incremental improvements, most companies also make some investments in radical innovations ('skunk works'). Firms in the existing regime may decide to sponsor a particular niche, when they think it has strategic potential (in the long run). As companies watch and react to each other's strategic moves, strategic games may emerge which suddenly accelerate the development of new technologies leading to 'domino effects' and 'bandwagon effects'.

If tensions exist, a radical innovation may take advantage and break through in mass markets. It then enters competition with the existing system, and

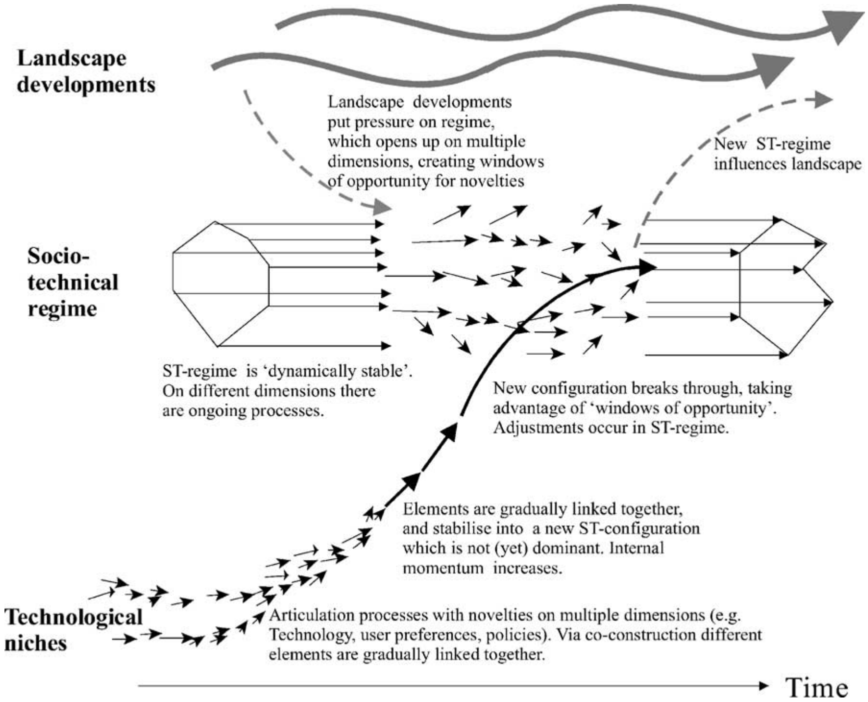

Fig. 9. A dynamic multi-level perspective on system innovations (Geels, 2002b, p. 110).

may eventually replace it. This will be accompanied by wider changes (e.g. policies, infrastructures, user practices). This is a period of flux, restructuring and Schumpeter's 'gales of creative destruction'. There may be entry and exit of new players in industry structures. Eventually a new system and regime is formed, carried by a network of social groups who create and maintain ST-systems. The new regime may eventually also influence wider landscape developments (see Fig. 9 for a schematic representation).

6. Discussion and conclusions

This article has made four contributions to the sectoral systems of innovation approach. The first contribution was to explicitly incorporate the user side in the analysis. Hence, it was suggested to widen the unit of analysis from sectoral systems of innovation to socio-technical systems, encompassing the production, distribution and use of technology. A second contribution was to make an analytical distinction between ST-systems, actors and institutions/rules. Making such analytical distinctions somewhat goes against usual practice in science and technology studies, which tends to emphasise 'seamless webs', boundary work and messy empirical reality. Although reality is complex, it is useful to make analytical distinctions, because it allows exploration of interactions between categories. This article explicitly conceptualised dynamic interactions between actors, rules and socio-technical systems in Sections 4 and 5. This way the article went beyond notions that everything is complex and inextricably linked up. A third contribution was to open up the black box of institutions and provide a dynamic sociological conceptualisation which understands human action as structured, but leaves much room for intelligent perception and strategic action. This perspective is particularly useful to analyse long-term dynamics (years, decades), e.g. the co-evolution of technology and society (emergence of new technologies, articulation of new user practices, changes in symbolic meanings). The fourth contribution was to address the issue of change from one system to another. To that end the article described a multi-level perspective, addressing socio-technical change at three different levels. Transitions come about when dynamics at these three levels link up and reinforce each other. This understanding of transitions is not only academically interesting, but also has societal relevance. Modern societies face several structural problems. Examples of these problems can be found in many sectors. The transport sector suffers from problems such as congestion, CO_2 emissions, air-pollution (small particles: NO_x). The energy sector suffers from problems such as CO_2 and NO_x emissions and reliability issues (oil). The agricultural and food sectors suffer from problems such as infectious disease (e.g. BSE, chicken plague, foot and mouth), too much manure, too much subsidies. These problems are deeply rooted in societal structures and activities. In order to solve such deep societal problems changes from one system to another may be necessary (Berkhout, 2002). An understanding of the dynamics of transitions may assist policy makers to help bring about these changes.

The conceptual perspective in this article is fairly complex. Can it be made operational for empirical research? The proof of the pudding is in the eating, i.e. use the perspective for empirical analyses of dynamics of socio-technical systems. In recent years, the multi-level perspective has been used in several empirical studies. It has been applied to the analysis of the transition from sailing ships to steamships (Geels, 2002a) and the transition from horse-and-carriage to automobiles and from propeller-aircraft to turbojets (Geels, 2002b). Belz (2004) used the perspective to study the ongoing transition in Switzerland (1970–2000) from industrialised agriculture to organic farming and integrated production. Raven and Verbong (2004) used it to analyse the failure of two niches in the Netherlands, manure digestion and heat pumps, because of mis-matches with regime-rules of electricity and agriculture. Van den Ende and Kemp (1999) applied the niche-regime-landscape concepts to analyse the shift from comput*ing* regimes (based on punched-cards machines) to comput*er* regimes. Van Driel and Schot (2004) used the multi-level perspective to study a transition in the transshipment of grain in the port of Rotterdam (1880–1910), where elevators replaced manual (un)loading of ships. And Raven (2004) used the perspective to study the niches of manure digestion and co-combustion in the electricity regime. Although the multi-level perspective is complex, these studies show its usefulness for empirical analyses. But these studies also increasingly point to a need to differentiate the multi-level perspective, to accommodate differences between sectors and industries. One way forward is to allow for different routes in systems innovations and transitions (Geels, 2002b; Berkhout et al., 2004). These routes may consist of different kinds of interaction between the three levels. One route could be rapid breakthrough. Sudden changes in the landscape level (e.g. war) create major changes in the selection environment of the regime. This creates windows of opportunity for an innovation to break out of its niche and surprise incumbent firms (Christensen, 1997). An example is the breakthrough of jet engines in and after World War II. Another route could be gradual transformation, involving *multiple* innovations. This route starts with increasing problems in the existing regime. This leads to a search for alternative technologies. The search does not immediately yield a winner, resulting in a prolonged period of uncertainty, experimentation, and co-existence of multiple technical options. Only after some time one option becomes dominant, stabilising into a new socio-technical regime. Yet another route could be a gradual reconfiguration in large technical systems. The new innovation first links up with the old system as an add-on, and gradually becomes more dominant as external circumstance change. An example is the gradual shift in the relationship between steam turbines and gas turbines in electricity production (Islas, 1997). At this stage these routes are merely an indication of a possible way forward. They indicate that the systems of innovation approaches have a fruitful life ahead of them.

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