

## CHAPTER 6

### *Technological change*

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*Contributors*

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Technology is implicated in global climate change in various ways—as a source of the problem, a possible solution, and an instrument of measurement and analysis. Coal-fired power plants and gasoline-fueled automobiles produce carbon dioxide emissions, the most important greenhouse-related gas. These emissions may be reduced, for example, by more energy-efficient combustion technologies, storing carbon dioxide emissions in empty gasfields, devising tools and methods to fertilize and irrigate crops more efficiently, or developing technologies that do not produce greenhouse gas emissions such as wind turbines and nuclear power. Technologies such as air conditioning and improved building design may enable people to adapt to climate changes.

This chapter focuses on the nature and the dynamics of technical change; how technology is shaped by social, economic, and political forces alike; and how, in the same process, technologies and technology systems shape human relations and societies. Such an understanding is vital if deliberate technological change is to be part of the solution to climate change problems.

Central to this understanding is the link between global climate change and what we will call evolving sociotechnical landscapes, which are part and parcel of overall transformations of societies. Particular technologies and artifacts are parts of larger systems and elements of a sociotechnical landscape. Their manufacture and efficient use depends on other technologies and skills that may or may not be available. They must compete with existing technologies that, unlike the new technologies, have benefited from scale and learning economies and from institutional adaptations. The diffusion of new technologies is connected not only with improvements in the technology compared to competing technologies, but also with the costs and availability of complementary technologies and with institutional changes in organization, ideas, norms, and values.

Differences among social science approaches to analyzing technological change are treated in the first section as building blocks for an overall framework. Perspectives from economics, sociology, and history provide powerful images of what technology is and does, but each image is only a partial picture. Our effort in this chapter is to note the strengths and weaknesses in each perspective and to find aspects that converge and support a broad and realistic understanding of technology and technical change. Within this convergence, we emphasize evolutionary and quasi-evolutionary approaches, which have contributed much to understanding technology and technological change. The second section, therefore, also examines the key role of coevolution of technological supply and demand. Dynamics and outcomes of technological changes are parts of the same process; each research emphasis yields insights but only partial explanations. The predictive capability of such research is strongest for incremental changes and situations where technologies have achieved stability. Evolutionary approaches are the most promising for the question of managing

technical change, the subject matter of the third section. The concluding section summarizes the main findings and draws out further perspectives.

### *Conceptualizations of technology*

The traditional meaning of the word *technology* is said to be the study of arts and crafts. The term referred to what, for instance, masons or painters should know in order to be good and qualified masons or painters (Singer et al. 1954). At the beginning of the nineteenth century, the knowledge of trades and skills became more and more standardized. The advent of engineering schools in the eighteenth and nineteenth centuries was another important ingredient of change. In the same period, the meaning of the term “*technology*” shifted from the study of arts and crafts to include and emphasize purposeful invention and, by implication, the strategic deployment of such inventions.

Although the idea of technology as artifacts (gadgets and gizmos) is still widespread in our culture, we will argue that a broader understanding has greater explanatory power in understanding the complexity of technology and its dynamics. Artifacts can be used without an indication of their history and their inner working; this is called “*black boxing*.” The material aspect of black boxing in modern household appliances is evident in the sleek surfaces that hide from view how the appliances work. The cultural aspect is exemplified by the absence of any need to inquire into the world behind the electrical outlet as described in Chapter 5 of this volume. (Also, see Vol. 1, Ch. 1 for other discussions of black boxing.) The division of labor contributes to the black boxing of technology in such a way that technology actually appears primarily as a set of tools. This division of labor in making and using tools dates from ancient times, but became very strong with the Industrial Revolution in the eighteenth and nineteenth centuries, and the increasing role of research and development (R&D) in the twentieth century.

Recent economics and sociology of technology have recognized the intellectual as well as political risks of treating technology as an exogenous factor, and attempt to endogenize it—with some success. Technology is studied as part of the world and its dynamics, suggesting that it may be a malleable aspect of social life. Although there is something hard, fixed, structuring about technology, these qualities are not attributes of technology as such. In Latour’s (1987) phrase, artifacts are *immutable mobiles*. Their immutability is the outcome of material and sociocultural configuring, not a property of the artifact as such.

*Conceptualizations of technology in different disciplines*

Various disciplines and subdisciplines studying technology take their own cross-sections of the complex whole that is technology. We may group the conceptualizations of technology in the literature into four clusters. These need not be competing alternative conceptualizations, but may be complementary. The boundaries demarcating them are seldom clearly defined; one often implies another. In our presentation of the clusters, we will also identify building blocks for an integrated conceptualization.

*Technology as tangible things and skills*

Technology can be thought of in a narrow sense, as *tools*. The traditional archeologist's interest in axes and arrowheads and the attendant idea of *Homo faber* man the maker, imply an anthropology that is very individualistic, that does not consider infrastructural technology, or what we will call extending the cultural anthropologist's notion of material culture, "the evolving sociotechnical landscape."

The idea of technology as tools also suggests the metaphor of technology as a *cannonball*. New technology is often thought of as coming in from the outside, diffusing, and being taken up for its overt function. This is also how impacts of technology are sometimes conceived: as dents or ruptures in society caused by the cannonball of technology impacting its walls. The cannonball view seems the natural one; for example, people regard the motorcar itself as a source of impacts.

It is true that most technology can be seen as tangible items: movable artifacts, often products for sale on consumer or professional markets; infrastructural technology (e.g., networks); unique technology, such as the Dutch Oosterschelde flood barrier; production technology; monitoring technology, testing technology, and instrumentation—each exhibits different characteristics in nature, dynamics, and impacts.

But technology is also stratified, in the sense that it is composed of materials and components, combined into devices and linkages that, in their turn, are combined into an overall working system. This is how modern technology is organized: a *configuration that works*. An underpinning systems view is important in effectively developing and maintaining technology.

The systems view includes elements such as skills and infrastructure. Engineers are confronted with this perspective in their professional activities. They ponder daily how to make such configurations, and make them work, how to maintain them in working order, and perhaps expand them. This view of technology, as configurations that work, captures the aspects neglected or at least black boxed by the focus on tools. The configurations can look like tools

(e.g., a natural gas combined-cycle turbine) but include the skills necessary to install and operate the turbine and manage the situations (including infrastructures, division of labor, and cultural norms) in which they can be handled productively, and will thus work.

This practical approach is often articulated as a sequence of hardware, software, and orgware. This has become an integral part of the systems approach, sustaining a concentric approach to the world with a technical artifact or system in the center. A further concentric ring, socioware, includes the societal embedding of a technology in concrete societal contexts as part of the development of technology. This is increasingly addressed when large, complex systems are designed. The concept of sociotechnical systems emphasizes that orgware and socioware are integral parts of a technology (Hughes 1983). For some technologies, such as nuclear technology and modern biotechnology, public reactions have forced developers to redesign their systems. Learning from these experiences, they sometimes anticipate public acceptability actively; in other words, they include socioware in the design and development of their technology.

For engineers and other hands-on developers, producers, and users, technology is articulated as a concentric configuration that works. This articulation includes a decision to speak of technology (and thus be responsible for its working) within a limited set of concentric circles only, and consider wider circles as environments or contexts in which the core machinery of the technology must function.

The concentric view also appears in the history and philosophy of technology (where it is sometimes further reduced to a history of ready-made artifacts). Researchers have paid attention to the influence of context and to overall socio-technical transformations of society. But the focus (and sometimes the arrow of causality) moves outward from the (novel) artifact or technology. White's (1962) analysis of the invention of the button and its impact on clothing, health, and society in medieval times is a good example. Other cross-sections are possible. Especially in studies of automation, the structure of the organization and the skills of the members of the organization are the starting point for analyzing working configurations. For infrastructural and network technologies, such as irrigation, the services that are part of the configuration can be taken as the starting point.

To put the point more generally, configurations that work cannot be demarcated from the rest of society in a simple and obvious way. Things and skills are part of routines, of patterns of behavior, of organizations. They work only because they are embedded in this way. Furthermore, their work is not limited to serving the need implied by their official function. As Douglas (1979) has pointed out, goods are wanted as means of communication within cultures as much as they are means to fulfill needs, or achieve goals (see Vol. 1, Ch. 3). In

other words, the concentric view reflects an important aspect of technology, related to engineers' practices, but it is also a partial view.

*Production technology: transformer of input into output*

Another conceptualization of technology emphasizes production technology, in contrast to the products made. Microchip technology, for example, is about silicon crystals and etching, not about the finished chips. This conceptualization has broader historical roots in the eighteenth-century mercantilist concept of technology as that which transforms raw materials into useful products. Against this backdrop, it is not surprising that the notion of production technology can be generalized to whatever transforms inputs into (desired) outputs, whether these are hardware, software, or orgware. Organizations can then be analyzed in terms of their production processes, whether the products are capital or consumer goods, services, or decisions (as in government bureaucracies). In all these cases, analysts can speak of the technology used for production.

Sociologists of organizations have suggested that technology actually determines the shape of successful organizations. It was thought that when the core technology (i.e. the intended production technology) of the organization is known, the shape and functioning of the organization can be designed around it. In the 1970s and early 1980s, this view shifted toward a more contingent idea of organizations. Technology was no longer seen as the key factor to explain form and functioning; more important was the environment. Mintzberg's (1983) work is a typical, and influential, example of this position. More recently, the idea of core business has been emphasized in the world of organization and business, as well as in organizational sociology. After years of diversification, businesses are going back to their core activities. With this emphasis on the core business, technology—in the sense of transformer—becomes more important too.

The concept of technology as whatever transforms input into output—the *transformer* view—has several implications:

- It sustains the use of technology in neoclassical economics as the determinant of the location of the production function (specifying the outputs of various combinations of labor and capital).
- The existence and shape of the technology is explained as derived from the fulfillment of a function. An existing reservoir of technological options, skills, and knowledge is assumed that can be drawn upon, more or less freely.
- The technology lies within the organization, or within the system boundaries. It is only because of these boundaries that its nature and dynamics can be traced.
- The transformer view can be used heuristically to analyze aspects of

technologies that are not contained within a single organization, for example, networks and infrastructural technologies. For electricity power generation and network distribution, Hughes (1983) has shown how the transformer view identifies load factor as a key aspect, not just in electricity generation and distribution (where it is a well-known issue), but in network and infrastructural technologies in general.

The added interest of the transformer view when looking at interorganizational networks is that it requires the analyst to identify the nature of the configuration that is employed by the network to produce outputs. Sometimes, such a network is managed by one or more of the actors involved. In other cases, the configuration emerges and stabilizes almost on its own, not according to the management plan (Joerges 1988b: 26):

Retrospective studies of LTS [large technical systems] show that they never develop according to the designs and projections of dominant actors: LTS evolve behind the backs of the system builders, as it were. It has been shown, too . . . that typically none of the agencies contained in LTS manage to form a somewhat complete picture of their workings. LTS seem to surpass the capacity for reflexive action of actors responsible for operating, regulating, managing and redesigning them in ways which, as social scientists, we understand poorly.

This is not to say that things will go wrong because the actual configuration is an unintended outcome of many choices and interactions. The challenge is to discover how such configurations emerge and are still productive.

At an even larger scale is the notion of organizing and technical capacities (see Chandler 1990 for firms, Porter 1990 for sectors). At a national level, "The network of institutions in the public and private sectors whose activities and interactions initiate, modify and diffuse new technologies may be described as 'the national system of innovation'" (Freeman 1987: 1). There is a clear technology policy interest in this notion, theoretically capable of specifying what determines the performance of nations. However, Lundvall (1988) and others have emphasized the strongly historical character of such national systems, implying that they cannot be changed at will. The case of Japan is particularly illuminating because of its modernization in the late nineteenth century and early twentieth century, which provided the basis both for its later war effort and for its economic performance in the 1960s and 1970s (Odagiri & Goto 1993). No easy recipe exists for transforming national resources into performance.

The abstract concept of technology is an assumption underlying the *production function* approach in organizational sociology and in neoclassical economics. In organization studies, the influential position is Perrow's (1970), who

took technology as the set of activities with which resources are transformed into output. This view has now become important with the increased interest in the services sector and with the emergence of software companies, systems consultants, and other providers of means to transform inputs into outputs, that depart from a classical, physiocratic, or industrial mode of production.

The conception of technology in organization studies is fully equivalent to the neoclassical economic conception of technology as the determinant of the location of the production function in the input factors space (labor and capital). A production function is a specification of all conceivable combinations of inputs to realize a certain output. If the capital input ranges from cheap (e.g., in construction work, shovels—which require many laborers) to a little more costly (fewer laborers with wheelbarrows) to expensive (one operator with a bulldozer), the producer can decide upon preferred capital investments for given labor costs. When technical change occurs, this is conceptualized as a change in location of the production function, for example, because bulldozers are now made more cheaply or require even less labor to handle. Technical change remains an exogenous variable. “Apparently, one main limitation of the production function concept is that it lacks a conceptualization of technology, per se. Its relevance is primarily to an aggregated level of analysis. This is a source of both its weakness and its strength.” (Sahal 1981: 22).

*Technology as a key aspect of the sociocultural/sociotechnical landscape of society*

In anthropological studies, archeology, and cultural studies, technology is used to refer to the artifacts, or sets of artifacts in a society, called its material culture (e.g., Hodder 1989, Lemonnier 1993). The notion of landscape can be used to capture the anthropological conception of technology. The *sociotechnical landscape* is a landscape in the literal sense, something around us that we can travel through; and in a metaphorical sense, something that we are part of, that sustains us. Although we will use the concept primarily at the level of societies, it can be applied just as well to the concrete organization of a firm (Gagliardi 1990) or to everyday life in households (Joerges 1988a).

In other disciplines, interest is increasing in what we call the sociotechnical landscape in the literal sense: geography, regional economics, industrial ecology (e.g., Socolow et al. 1994). In addition, recent interest in technology, general philosophy, and sociological specialties such as the sociology of culture and the sociology of everyday life, has produced important analyses of sociotechnical landscapes in the metaphorical sense. For example, analyses of a world that makes high speed possible (Virilio 1984) and of the brave new worlds of medical technologies that change our view of ourselves. The two senses of sociotechnical landscape are inherently linked. As mentioned earlier, artifacts not only have immediate functions, but they are also “needed for making visible



and stable the categories of culture" (Douglas & Isherwood 1979: 59).

The motorcar is not an isolated artifact, but the label for part of our socio-technical landscape, made up of steel and plastic, concrete (the roads), law (traffic rules), and culture (the value and meaning of personal mobility). Sørensen (1991) emphasized this point in his study of the introduction of the motorcar in Norwegian society. As in many countries, the Norwegian car is a culturally and politically constructed symbol of modernity, associated with notions of freedom, democracy, and masculinity (see also p. 336). Politically, the car was labelled as a luxury (and so taxed), but culturally it became a necessity, a basic ingredient of everyday life. Interestingly, the car also grew into a critique of everyday life: a means for getting away from daily routines, literally and mentally, and a symbol for a more adventurous life. In this way, the car became part of the symbolic order of Norway, even though Norway does not produce motorcars itself.

There were other parts to the story. A growing part of household income was spent on motorcars. Experts (highway engineers, transportation economists, and planners) imported visions about cars, mainly from the United States, and developed the necessary infrastructure. Gradually, more and more efforts were demanded from users and local authorities to adapt everyday life to this symbol. The result was the gradual physical transformation of Norwegian society. This is not just a story of the introduction of an artifact. A whole society was changing, from low mobility and little infrastructure, to high mobility; cars (as artifacts and as symbols) were part of that transformation.

Combining the artifact view with this landscape view, Mumford (1966) conceived of technology as a *megamachine*. He made two important points about technology:

- Technology is not an external driver of societal transformations, but part of them.
- Configurations combining the social and technical should be considered in order to understand society and technology.

Mumford introduced the notion of a megamachine to describe how people are part of the sociotechnical setup, and he considered cities to be primary examples of megamachines. What is "termed the Machine Age or the Power Age, had its origin, not in the so-called Industrial Revolution of the eighteenth century, but at the very outset [in the age of the pyramids] in the organization of an archetypal machine composed of human parts" (Mumford 1966: 11). For megamachines, the juxtaposition and assemblage of forces will partly be the unintended outcome of many interactions, rather than the effect of an overall design by a prince and his engineers (Latour 1988).

*Technology as a symbol and as an ideology*

Technology has become an important element of the self-image of Western culture. Because it has been, and continues to be, a key factor in transforming societies, it has become associated with modernity, progress, and rationality. These associations are carried by the idea of technology in official declarations and in debates, and when technology legitimates particular roles, actions, and policies. When leaders of nations expound on the importance of technology, they may refer to specific technologies and policies, but they primarily convey the message of being modern and progressive.

Why do we include such symbolic use, confined to spoken and written texts, in our attempt at conceptualization of technology? Technology has a definite cultural aspect. The motorcar stands for a cultural complex, and people understand a reference to the motorcar as not being about the class of actual motorcars in use (say, in Norway), but about this cultural complex, and about the problems caused by the motorcar. So there is a symbolic element to the motorcar.

Historians have been sensitive to symbolic technology and its very real role in continuing transformations. Leo Marx has identified the invention of the general notion of technology as part of overall changes around the turn of the century, related to the emergence of large technical systems (such as railroad and electricity networks) and large corporations controlling the economy (Marx 1994: 18–19):

The concept refers to no specifiable institution, nor does it invoke any distinct associations of place or of persons belonging to any particular nation, ethnic group, race, class, or gender. A common tendency of contemporary discourse, accordingly, is to invest "technology" with a host of metaphysical properties and potencies, thereby making it seem a determinate entity, a disembodied, autonomous, causal agent of social change—of history.

As a symbolic term, technology has influenced scholarly studies and intellectual debate by supporting a view of technology as exogenous—the cannonball view of technology, as we called it above.

Other important functions of symbolic technology can be recognized. A specific division of labor is predicated on the idea that there is something called technology, separate from organizations and sociotechnical landscapes. Thus, technology supports a diffuse social contract between technologists and society. Technologists are mandated to work on technical progress (and thus achieve progress in general). They have relative autonomy to work on a specific technology so long as they work toward progress and can be seen to work toward progress (Van Lente 1993).

More generally, in the nineteenth and twentieth centuries, support for

concrete technological developments has been mobilized and legitimated by presenting them as instances of technological progress. Advocates of specific technologies have argued, and often continue to argue that hindering the development of these technologies is wrong, even immoral, because it would go against technical progress (needed, for example, to develop renewable energy systems). On the other hand, opponents of the same technologies have mobilized countervailing powers by referring to progress as the overarching goal, and depicting the particular technology at issue as a threat to progress (say, because of potential damage to human well-being or the environment).

Thus, in addition to the division of labor, there is now a struggle about the distribution of praise and blame (Douglas 1992). Struggles about specific technologies, for example, chemicals, nuclear energy, and biotechnology, will refer to symbolic technology in general as well, positively or negatively. In addition, an intellectual and political debate centers around the status that technology (and thus technologies) should have in our societies. Historians, sociologists, and philosophers are taking up such issues in their analysis. For example, Beck (1992) argued that the central societal and political issue of modern societies from the nineteenth century onward, the division of labor and distribution of income, has been pushed into the background by the new issue of distribution of risk—in which technology is heavily implicated.

Technology as symbol is an entrance point to important issues. Public policy debate about technology is not about preferences and needs, independent of technologies, but is already shot through with views on technology and its possibilities. So the question of orienting and steering sociotechnical change is intimately linked with culturally defined possibilities, and which division of labor, cultural codes, and storylines, have become embedded. To capture these aspects, the next subsection introduces the concept of *technological regime*, which combines such rules and cultural patterns with stabilized material culture. This is how we have already spoken of the motorcar as symbol and integrating part of the motorcar regime.

In a view combining the landscape and symbolic concepts, technology can be seen as a *seamless web*. Hughes (1986) speaks of a seamless web to indicate how very different elements (artifacts, entrepreneurs, networks, banks, regulations, users) join together in technological developments, in particular in large technical systems such as electricity networks. The idea of a seamless web also implies that the evolution of technology and the evolution of society cannot be separated, and should be thought of in terms of coevolution.

*Conceptualization of technology and the dynamics of sociotechnical change*

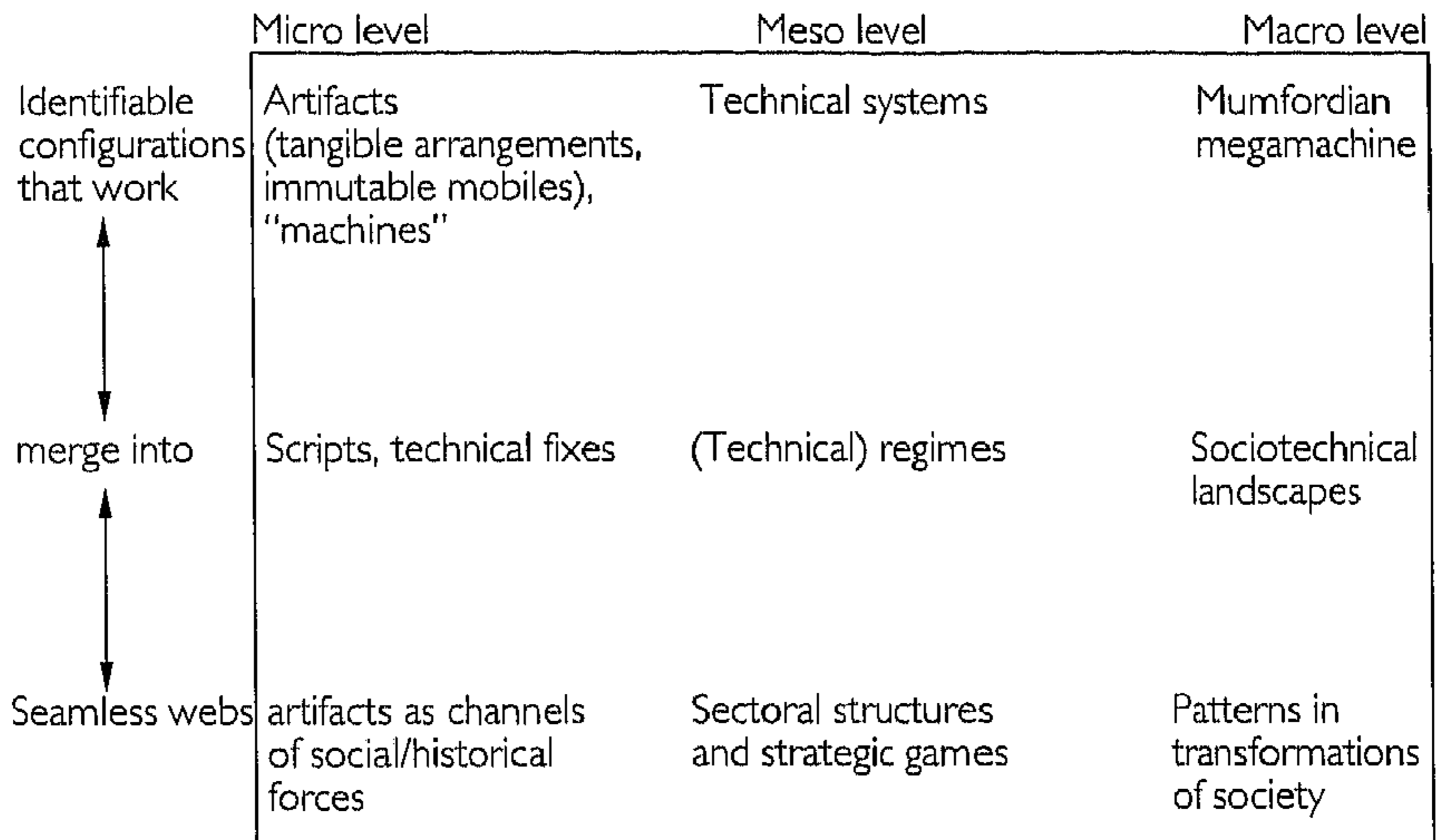
The view of technology as configurations that work tends to center attention on the artifact and the technologist who introduces novel technology, emphasizing technology as the introduction of novelty, or new combinations (Schumpeter 1934). However, emphasizing the artifact and the technologist runs the risk of underconceptualizing the social environment into which the novelty is introduced. Technologists (in a typically modernist attitude) tend to see their environment only in terms of opportunities and constraints for the introduction of their new project. But, in fact, the social environment has its own dynamics, and it has already shaped the opportunities for, as well as the ideas about, the novel configuration. Therefore, structural aspects of the environment of technologies, and existing systems and sociotechnical landscapes, must be taken into account.

Technical groups and their social environments create stabilized interdependencies that shape further action—including work toward new technology. To develop a conceptualization of technology that does justice to these phenomena, we will use the concept of *regime* (Rip 1995) or *technological regime* (Kemp et al. 1994). 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 artifacts and persons, ways of defining problems—all of them embedded in institutions and infrastructures. Regimes are intermediaries between specific innovations as these are conceived, developed, and introduced, and overall sociotechnical landscapes.

Regimes are outcomes of earlier changes and they structure subsequent change. Novelty evolves within existing regimes and sociotechnical landscapes, starting at the micro-level of local practices. It spreads over time, partly by accommodating to existing regimes; eventually it may irreversibly transform the sociotechnical landscape.

The introduction of novelty has been studied in great detail. However, the adoption of novelty is decisive for society, not its introduction. Adoption is an active process, and has elements of innovation itself. Individual behavior, organizations, and society have to rearrange themselves to adopt, and adapt to, innovation. In this sense, the introduction of a new technology is an unstructured social experiment.

The adoption and diffusion of a technology result in decreased uncertainty regarding its actual capabilities, performances, and interdependencies—technical as well as social. In turn, this leads to some standardization (Foray 1993, Foray & Freeman 1993). From these processes of adoption and standardization, irreversibilities emerge. In fact, to create a robust technology, some irreversibility (i.e., inflexibility) must already be built in, in the sense that the artifact or



**Figure 6.1** The multilayered backdrop of novelty and irreversibility.

system cannot be easily dismantled after it has been put together. Implementation, adoption, use, and domestication of technology create and maintain social and technical linkages that are hard to undo. The motorcar is deeply embedded in industrialized societies, creating a web of interdependencies that make it difficult to replace by other means of transport.

Irreversibility, once achieved, is what makes a technology hard, difficult to change, and a structural factor itself.

The emergence of irreversibility also reduces complexity. Features of a technology and the articulation of demand for it become stabilized, so that the technology becomes an accepted part of the landscape. It can be black boxed by labels—such as electricity or the motorcar—that conceal the complexities involved. The use of such labels stabilizes the new order, and is thus part of technology and its dynamics (see also Vol. 1, Ch. 1).

The dynamics sketched here focus on a technology evolving against a backdrop of systems, regimes, strategic games, and slowly changing sociotechnical landscapes of which it is already a part. The time axis structures the conceptualization. Charting the backdrop without this emphasis on change over time reveals the scope of the various dynamics and how they are located in the seamless web. A two-dimensional scheme captures most of the important aspects (Fig. 6.1).

The horizontal axis sets out configurations of increasing scope. Although it reflects the concentric view, it does not imply a modernistic approach of introducing novelty against the obstacles of the environment (see also Ch. 5).

All levels (here indicated as micro, meso, and macro) play a role. For example, stabilized meso- and macroconfigurations, such as a motorcar regime or factory-based regimes of production and accumulation, may stimulate incremental innovations, and hinder so-called architectural innovation (Abernathy & Clark 1985).

Down the vertical axis, the configurations become more heterogeneous and reflect the seamless-web character of technological change. If fluid and heterogeneous combinations are taken as the starting point, particular configurations appear as nodes in the web that derive their character from the way they function in the web. For example, numerically controlled machines in the workplace are recognized as channels for the struggle between management and labor (Noble 1984).

Within the evolving backdrop visualized in Figure 6.1, processes of novelty creation and irreversibility occur. Technology, clearly, does not fall into one neat category of the social sciences. It cuts across levels and categories so that no one discipline, oriented to its own methods and ideals of explanation, can capture the complexity. So social scientists abstract those aspects of technology that fit their respective disciplinary models. Sociology looks at social configurations, economics at cost efficiency. Both historians of technology and economists are divided over whether they should focus on technology as artifacts or as (embodied) knowledge, whereas general historians and macrosociologists might take technology primarily as a symbol of rationality. Figure 6.1 illustrates how there can be such a variety, and at the same time justifies the attempt to identify building blocks, cutting across disciplinary categories.

Figure 6.1 also indicates that there will be the variety of technologies, as related to their location and dynamics (and the cross-section that is taken in the scheme), rather than to intrinsic properties. The dynamics of change, and the links with regimes and sociotechnical landscapes, will be different for motorcars, chemical plants, and irrigation systems. Utterback (1994: 123) notes how useful it would be "if we could classify products and technologies into sensible groups, between which patterns and details could be observed. Unfortunately, scholarship has not provided any such meaningful and simple classification . . ." So he limits himself to what he calls "the two extremes: complex assembled products on the one extreme, and homogeneous, nonassembled products on the other."

Going further in this direction, we can differentiate technologies as to how they are located in and linked up with their environment:

- moveable artifacts, often products for sale on consumer or professional markets (Utterback's nonassembled products)
- localized plants and production technology generally (one form of Utterback's assembled products)

- infrastructural technology (e.g., networks), which are to some extent collective goods
- dedicated, one-off technological systems, such as the Dutch Oosterschelde flood barrier
- monitoring technology, testing technology, and instrumentation (often of key importance, but not always taken up in the analysis).

The dynamics of change are related to linkages, regimes, and the shape of the sociotechnical landscape. The idea of architectural innovation and distinctions between radical, and incremental innovation (Abernathy & Clark 1985) depends on the nature and extent of the linkages that have to be broken.

Developments in a vertical direction, toward ever higher performance, as in the race to develop faster and higher-capacity microchips, are possible when strategic considerations are dominant, and they contrast with developments in a horizontal orientation, toward new uses of existing technology and innovations during the diffusion process. Vertical dynamics can have a life of their own, not because technological developments are autonomous, but because efforts of actors are geared toward the goal of achieving the next generation. Moore's law, that memory chips will increase fourfold in power every three to four years, is a case in point: it is not a law of nature, and its empirical regularity derives from the efforts of actors, stimulated by their comparisons with the milestones predicted by the so-called law (Rip 1992, MacKenzie 1992).

*Technical situatedness* and interrelatedness of technologies is another overall dynamic. The introduction of new technology is heavily context dependent, not only because of the learning that has to occur, but also because of the socio-technical linkages and regimes that exist already, and that might be created. Promising stories about and demonstrations of so-called smart houses are intended to bring about a future with all-electronic houses. The actual trajectory toward such a future depends on the cumulative effect of moves taken now, in the context of the present regimes.

### *Long-term and macro-development*

The multilayered system depicted in Figure 6.1 evolves over time. The various ways of tracing these changes and highlighting the transformations that occur recall the different conceptualizations of technology. One way of tracing transitions is to highlight the organization of the production of technology. For example, the engineering and craft-based industrial revolution of the eighteenth and early nineteenth centuries was succeeded by increasingly scientific technology from the late nineteenth century.

Another way is to focus on materials and sources of power that are widely

used. For example, technology was based on the use of water and wind as sources of energy, and wood and stone as construction materials, until the seventeenth and eighteenth centuries. Then additional sources of energy (coal) and materials (iron) became important, without replacing water, wind, wood, and stone. From the early twentieth century onwards, more flexible energy sources (oil, electricity) became available. New kinds of materials, designed for specific functions, came into their own from the 1950s onwards.

However, for understanding overall dynamics of technological development and the kinds of conditions and incentives that are at work, technology characterization in terms of basic materials and energy sources is insufficient. The organization and context of the production and use of technology, its sponsors, and its linkages with social institutions are important as well.

Although it is commonplace to speak of the impact of technology on society, the impact is really related to industrialization, rather than to a specific technology. The Bessemer converter for making steel, itself shaped by social and economic factors, was part of overall transformations of the steel industry, the railways, and construction, and this particular piece of technology cannot be singled out as the cause (Misa 1992; also Elam 1993 for the case of Korean steel plants in the 1980s). Similarly, impacts on the environment are not so much impacts of a technology as of industrialization, transport, agriculture, and urbanization.

A few authors have attempted to trace technological developments of the past two centuries as an integral part of larger sociotechnical transformations. Freeman & Perez (1988) arrange their overview according to so-called Kondratiev waves with a 50-year cycle, but that is not essential (see Grübler 1994). The important point is that surges of interrelated innovations occur, not of their own accord but because there are strong economic and social factors at play that serve as prolonged containment first and as unleashing forces later.

According to Freeman & Perez, between the 1830s and the 1890s, steam engines, steamships, iron and steel production, machine tools, and railway equipment were the carriers of growth, supported by the key factor industries of coal and transport, offering abundant supply at declining prices. Within this overall framework, newly emerging sectors such as steel, electricity, gas, synthetic chemicals, and heavy engineering can be identified that (in retrospect) laid the foundations for the next period. All these developments were embedded in, stimulated by, and to some extent made possible by, broader transformations. Further development of mechanization and factory production was related to:

- growth in the size of firms and markets
- new legal forms (limited liability and joint stock companies) that allowed new patterns of investment, risk taking, and ownership



- growth of transport and distribution, such as postal services
- financial services
- establishment of training of engineers and skilled workers
- international regimes (e.g., the Pax Britannica, which allowed transport and free trade).

The next period distinguished by Freeman & Perez, from the 1890s to the 1940s, had a very different complexion. Limitations of iron as an engineering material (strength, durability, and precision workability) were partly overcome by the universal availability of cheap steel and alloys. Limitations of inflexible belts and pulleys, driven by one large steam engine, were overcome by unit and group drive for electrical machinery, overhead cranes, and power tools, permitting vastly improved layout and capital saving. Standardization facilitating worldwide operations occurred, linked to the emergence of giant firms, cartels, trusts, and mergers. Monopoly and oligopoly became typical. Regulation or state ownership of natural monopolies and public utilities was imposed. Banking and finance capital became concentrated. Specialized middle management emerged in large firms.

The main growth sectors were electrical engineering, electrical machinery, cable and wire, heavy engineering, heavy armaments, steel ships, heavy chemicals, synthetic dyestuffs, and electricity supply and distribution. Other smaller but rapidly growing sectors also emerged: automobiles, aircraft, telecommunications, radio, aluminum, consumer durables, oil, and plastics. It was also a world of structural societal changes, including imperialism and colonialism, the First World War, and destabilization of international financial and trade system leading to a world crisis and the Second World War. Throughout this period, there was rapid growth of state and local bureaucracies, and of white-collar employment. Distribution became important; department stores and chain stores emerged. Education, tourism, and entertainment expanded rapidly, and elementary education became universal in the Western world.

The Freeman & Perez description demonstrates how technologies and sectors that emerged already within the regimes of a previous period came into their own in the next period. Automobiles, aircraft, consumer durables, and synthetic materials were relatively new developments in the 1920s and 1930s, but by the 1950s and 1960s, the subsequent period distinguished by Freeman & Perez, they had become dominant. The abundance of cheap energy, especially oil, was the key factor in new production processes, but also in the new patterns of industrial location and urban development allowed by the speed and flexibility of automobile and air transport.

Later in this period, which according to Freeman & Perez continued into the 1980s, newly emerging technologies and sectors—computers, radar, numerically controlled machine tools, new drugs, rockets and missiles, microelectron-

ics, advanced software—modified this picture. Overall developments in this period can be characterized as much more of the same: government bureaucracies continued to expand in the welfare and warfare state, education continued to spread at increasingly higher levels, professions and services continued to grow. Only toward the end of the period (as Freeman & Perez distinguish it) did growth, as well as the confidence in growth, hesitate. Diseconomies of scale appeared, alongside inflexibilities of the factory-based regime and limitations of hierarchical control. To the list of factors mentioned by Freeman & Perez could be added recognition of resource limitations and the vulnerability of the environment, which set a new agenda for governments and firms. At the same time, the promise of new information and communication technologies was recognized, and speculations about the global village appeared. Freeman & Perez take this as the starting point for their characterization of the new period, from the 1980s and 1990s onward, as the information and communication Kondratiev wave.

Useful insights can be gained by arranging sociotechnical transformations into distinctive periods. But an analyst should also consider secular changes. The successive shifts of key factors from mechanics to energy to information have often been taken as indicative of a trend toward decreasing emphasis on material goods. This may be wishful thinking, however, given the continued importance of mechanics and energy as the necessary substrate for information and communication.

Three long-term trends can be identified as important in understanding the recent evolution of technology and society, as well as the present situation:

- Mechanization, including early versions of automation, for example mechanical calculators and punch card machines (Giedion 1948). This is often incorrectly viewed as a force by itself. Nevertheless, the trend appears to be dominant, at least up to the present.
- Development of technologies for regulation and control, of production processes, of organizations, of society in general. Beniger (1986) has argued that the new information and communication technologies should be seen as a response to the control crisis that emerged because of the rapidly growing system of industrial production, transport, and mass consumption after the middle of the nineteenth century.
- The increasing role of software in handling hardware. Software development and use in computer technology is the obvious example, with the advent of programming languages in the late 1950s as the key step. A broader concept of software includes the advent of operations research and of traffic engineering in telephone networks. The design and disciplining of activities and organizations on the basis of blueprints are also software in the broad sense. In common with computer software, gener-

alized software qualifies as technology. The broader notion of software links up with the analysis of historians and sociologists of how people, organizations, and society are monitored and disciplined with the help of technology (Foucault 1975).

*Technology choice?*

The emergence of technology policy, technology assessment, and the recognition of controversies about new technologies are all indicators of reflexive technological development. Of course, there has always been conscious consideration of which technologies should be developed and used, but this occurred ad hoc and often without attention to the nature and dynamics of technological development. Moreover, diagnosis of technology in society is no longer a privileged activity of a few social scientists, philosophers, and concerned intellectuals. It is now a matter for both popular discussions and meetings of heads of state. Such discourses may not always take the complexities of technological developments into account, but their effect is to keep technology on the public and political agendas.

Diagnosis of technology raises the question of whether people have the technology, and the sociotechnical worlds, that they really want. This is a complex question, because people may not know what they really want before they actually experience what they have got. If technological developments are truly irreversible, it may then be too late to shift. Even if people do have clear preferences, say, for environmentally benign technologies and a world without climate change, they may not be able to bend the dynamics of technological development in the direction they desire. This is not only a matter of power (Can society bend?), but also of information (What will be the outcome of technological developments that society sets in motion, or modulates?).

The economics literature often argues that intervening in markets is counterproductive. Against this view, two reasons are advanced in favor of intervention and attempts at orientation. One is analogous to the market failure argument, and asks for measures to ensure that coevolution processes are functioning well. The other is about promoting desirable outcomes or, at least, avoiding undesirable outcomes.

Policy actors such as governments often try to orient technological developments, although this may be controversial. To justify intervention, we need a robust theory of technological change and its outcomes. Present theories add up to a patchwork quilt at best. The literature to be reviewed in the next section turns out to focus strongly on the private for-profit sector, neglecting other actors and domains involved in the coevolution of technology and society.

*Understanding dynamics and outcomes of technical change*

Technical change can be studied in a variety of ways, from the history of artifacts to large-scale transformations of sociotechnical landscapes. We have illustrated the importance of taking a broad view and have posited good reasons to look at coupled changes of artifacts, technologies, and regimes, as well as larger and more long-term changes of regimes, sociotechnical landscapes, and overall transformations of society. In this section, we look at these changes as outcomes of the dynamics of technical change.

*Dynamics of technical change*

The voluminous literature on determinants of innovation focuses on identifying factors responsible for, or conducive to, success and failure. This perspective is of the manager of a firm for whom the economic success of an innovation is crucial. As a consequence, the eventual shape of the technology can be considered a side effect, the main effect to be realized (by the manager) or explained (by the economist) being a successful firm. The subtitle of Utterback's (1994) book *Mastering the dynamics of innovation: How companies can seize opportunities in the face of technological change*, reflects this perspective, but adds an important angle: technical change happens to a large extent outside the (individual) firm and belongs to the threats and opportunities in its environment.

The study of innovations is but one entrance point to the dynamics of technical change. The thrust of our analysis will be to show the emergent patterns and dynamics of technical change beyond innovation itself. In doing so, we draw on a recent report, *Technology and the economy: the key relationships* (OECD 1992), which provides an excellent overview.

The overall pattern of technical changes is one of coevolution. When firms are the focus, this coevolution is that of supply and demand. When technology is foregrounded, coevolution becomes a more complex phenomenon. By focusing on the relative nonmalleability of technology, we can capture a key feature (compare the general point of emerging irreversibility, above). Next we discuss quasi-evolutionary and sociotechnical theories of the dynamics of technical change to explain the relative nonmalleability.

*Innovation and adoption journeys*

The activities and strategies of the immediately involved actors, firms, and technology organizations are clearly important for the dynamics of technical change. Actors' strategies are predicated on their own concerns about what is conducive to success and on their perception of the environment. Innovation

studies have catered to these concerns in trying to identify success factors. The other main interest of innovation studies has been to highlight perceived trends, for example the shortening of the time period separating scientific breakthroughs from first application—with the implication that firms should become ever quicker on their feet.

Such attempts to find determinants of success are undermined by the recognition of contingency. Van de Ven et al. (1989), in their pathbreaking study of actual innovation processes, stressed the heterogeneity and contingency of the process. It is an innovation journey, with setbacks and new ventures, rather than the execution of a plan.

The question of when to invest in innovation cannot be answered simply. The many risks and uncertainties make cost-benefit calculation difficult and sometimes completely irrelevant. To maintain a market share or to remain abreast of future technological development, firms may be willing to invest in developing a new technology, even if the returns, at the time, appear to be negative. The notion of a next generation of technology, for example, in the case of semiconductors and integrated circuits, is an important reduction of complexity guiding the strategies of firms at the so-called technological frontier.

User-producer interaction in innovation is seen as an important item in explaining success (Von Hippel 1988); it also introduces further contingency. The producer has considerable interest in drawing on the user's learning process, but then becomes dependent on what is being articulated at the user's side. A similar point has been made by Leonard-Barton (1988) for the learning cycles involved in implementation.

In general, contingencies are related to inherent uncertainties in novelty creation and to linkages with actors other than the firm itself (or, within the firm, linkages of an R&D department or a project team to other parts of the firm). Because of the dependencies involved (whether recognized by the firm itself or not), the firm cannot control the innovation process.

Every act of technology adoption (from implementation to acceptance in a local situation) involves certain transformations and is thus innovation in itself. In the case of the spread of technology to other firms and organizations, two patterns have been distinguished:

- *disembodied diffusion*, originating in the externalities that characterize the innovation process and the research spillovers that occur when the firm developing a new idea or process cannot fully appropriate the results of its innovation
- *embodied diffusion*, equipment-embodied diffusion (purchase of machinery, components, other equipment), and knowledge and skills diffusion.

Disembodied diffusion takes place through the spread and uptake of information, knowledge, and intelligence, that is, information of a strategic

character. Mansfield (1985) showed that, on average, information concerning development decisions for a major new product or process was in the hands of some rival firms within 12–18 months after the decisions had been made. But, as he emphasized, the rapid spread of information does not lead to quick imitation, because of the necessity of learning by using. The importance of learning by using has been emphasized by Rosenberg (1982) and is now widely recognized as important. The recognition that adoption is not automatic and that there are costs involved has led to consideration of the so-called absorptive capacity in a firm, organization, or country. R&D can then be oriented, not to innovation, but to improve the capacity to anticipate, follow, and take up future developments. Nelson & Winter (1977) argue that, for firms to be able to use freely available knowledge, they often have to invest in R&D. Performance in basic research is “a ticket of admission to an information network” (Rosenberg 1990: 71). Adoption or imitation costs thus depend crucially on the technological level achieved by a firm, technology organization, or country; building up such a level and maintaining it is itself a costly investment. Thus, small and medium-sized enterprises have a problem, which will be smaller when they can participate in the right networks. For less industrialized countries, the problem may be chronic, unless they can exploit a window of opportunity.

Another economic issue of technical change derives from the nature of knowledge as a nonconsumable, and in that sense a public, good (where consumption by one does not preclude consumption by someone else). This creates the possibility of spillovers: the production of knowledge yields more benefits than can be captured by the producer. In fact, in some sectors, private industry publishes some of its research findings in scientific journals. The basic point, that outcomes of inventive activity cannot be fully appropriated, can lead to other patterns as well. When R&D efforts by firms generate externalities that affect the decisions of other firms and industries, overall effects are created at the collective level, and interorganizational networks emerge, exactly to capture the collective effect. Sectors such as electronics, with systemic technology, have high spillovers, many interactions, and a high rate of innovation (Levin 1988).

Different types of R&D and innovation, with different characteristics that could make them appropriable imply differences in ease of diffusion and adoption of innovations (cf. also Teece 1986). Nelson (1980) has drawn a distinction between two types of technological knowledge. One relates to basic upstream research (how things work in general) and the other relates to operative techniques (how to make things that are specific to the task at hand). The first has characteristics of public goods, the second much more limited applicability. An intermediate category of generic, enabling, or platform technologies underlies innovations in a variety of technologies. Adoption and diffusion follow different patterns in the different categories.

Diffusion of embodied technology exhibits its own patterns. One pattern is visible in the differences across industries. For example, in the United Kingdom, six core manufacturing sectors (metals, electrical engineering, shipbuilding and offshore engineering, vehicles, building materials, and rubber and plastic goods) account for two-thirds of all innovations, and these innovations are also used in other sectors (Robson et al. 1988). Japanese industries are more dependent on technology from key indirect technology sources and more able to diffuse technology across industrial sectors (Davis 1988). Market structure also plays a role; innovation suppliers in an oligopolistic market for technology may limit diffusion.

Choices at the level of the firm reflect patterns and developments at the collective level. Standard diffusion theory (e.g., Mansfield 1968) emphasizes how the rate of adoption of new technology will be affected by the age of the existing capital stock and by sunk cost. Firms' expectations of the path, and the pace, of future technical and market change are important.

One implication is that so-called delays in adoption (the term "delay" suggests that adoption is the obvious and rational choice) may well be rational: delay avoids costs associated with the introduction of new technology and waits for benefits of improved performance through incremental innovation. Early adopters, on the other hand, may create a critical mass and a pool of skilled labor, at their own cost. When this has occurred, the rate of adoption changes. As Metcalfe (1990) emphasized, there will be strategic considerations of different kinds (including conscious choices to be leader or follower).

If the technology rather than the firm is the focus of analysis, other aspects of diffusion come into the picture, for example, the complementarities and multiplier effects of large technical projects, and the way that diffusion is shaped by whatever technical systems and regimes are present. The next subsection summarizes the main findings of technology-focused studies.

#### *Technical complementarities and networks*

Production technologies are complex systems of interdependent parts: change in one of these parts requires sometimes costly system changes, referred to as *costs of interrelatedness* (Metcalfe 1990). This point can be generalized to technical systems, with several implications. The greater the interrelatedness in an existing technological system, the less likely that a further innovation will be compatible with it, unless it is actually designed for this system. In other words, the direction of incremental and process innovations shifts over the lifecycle development of system technologies, such as in the automobile industry (Abernathy 1978).

Interrelatedness can be actively sought. At the level of generic technologies, *technological fusion* may occur (Kodama 1990), resulting in new technologies

(with new rules and procedures) based on merging of previously distinct ones, e.g., mechatronics.

Another aspect of interrelatedness is how the effectiveness of innovation depends on the availability of complementary technologies (Rosenberg 1982). This point can be broadened in two ways. One is to consider the technologies implicitly available in the sociotechnical landscape: the all-electric house is one example, and researchers can analyze the emerging all-electronic world in a similar way. The other broadening is to consider intersectoral complementarities. Amable (1993) identified such complementarities as a key factor in wealth creation. Countries such as Germany and Japan were shown to benefit greatly from the complementarities among information technology and medium-technology industries that use information technology as an input of production. Islands of high technology, cut off from the rest of industrial base, retard diffusion and create structural problems for other industries.

These considerations go some way to explain the productivity paradox of the introduction of new information technology: although intended to increase productivity, no such effect can be measured (Edwards 1995). Insufficient complementarities are part of the explanation. Also, the systemic character of innovation introduces lags, in the sense that mutual articulation and adaptation processes are necessary, and that such learning processes take time (Foray & Freeman 1993: 104). In addition, on the adoption side, the utility of a new technology for an adopter increases with the number of adopters already using it. The effects of these network externalities (or dynamic externalities) are especially visible when the cost of adoption is high (as in information technology). As the number of adopters increases, so does the availability of skilled labor and maintenance and spare part costs—collective learning at the system level. Although these considerations explain the paradox of information technology, the points are general, as is clear from the analyses in Foray & Freeman (1993).

Including outcomes of technical change in our discussion is unavoidable because of the feedback and feed-forward relations in the dynamics. Sociotechnical linkages further imply that the regional level, as a geography of externalities, is important, and that network effects may not result in optimal technology and optimal performance over time: there will be lock-in (path dependencies) and possibly inferior technology.

Technology-related linkages can also be found in strategic alliances and other interfirm agreements. Increasingly, such agreements include actors other than firms, and various kinds of agreements are made in both the precompetitive and competitive spheres. According to Chesnais (1988), protecting key technologies and creating complex innovations are the main goals. Such linkages are part of emerging networks, a phenomenon that attracts increasing interest among researchers (DeBresson & Amesse 1991). A *network mode* of



interaction (Imai & Itami 1984) has specific characteristics; it is not a hybrid or transitory form between the poles of market and hierarchy. One diagnosis is that ". . . the complexities of scientific and technological inputs, the uncertainty of economic conditions . . . made hierarchies a less efficient way of responding to market imperfections" (Chesnais 1988: 84). Network relationships are easier to dissolve than hierarchies, sunk costs are smaller, and commitments are less definitive (Porter & Fuller 1986).

Firms often prefer the network mode (OECD 1992). A key feature of networks, once they exist, is the occurrence of learning. "A basic assumption of network relationships is that parties are mutually dependent upon resources controlled by another, and that there are gains to be had by the pooling of resources . . . As networks evolve, it may become more economically sensible to exercise voice rather than exit. Expectations are not frozen, but change as circumstances dictate" (Powell 1990: 13). Firms with experience with the network mode may actually choose this mode as learning experiments (Ciborra 1991).

Engineers, scientists, and others involved in technical change have their own networks, effective because they are informal (Hamel et al. 1989). Such networks are carriers of the important tacit component of technology. "Tacitness refers to those elements of knowledge, insight and so on, that individuals have which are ill-defined, uncodified and unpublished, which they themselves cannot fully express and which differ from person to person, but which may to some significant degree be shared by collaborators and colleagues who have a common experience" (Dosi 1988: 1126). Sharing such tacit knowledge, and informal networking in general, follows fairly identifiable patterns based on the assurance of reciprocity and the fair, albeit nontraded, exchange of knowledge. The success of formal agreements in which technology is involved depends heavily on the quality of the informal networks.

#### *Coevolution and the nonmalleability of technology*

The existence and importance of technical linkages, complementarities, tacit knowledge and learning imply that we cannot have whatever technology we wish. Constraints are related to the nature and dynamics of technical change. This is not to say that the ideology of technology push should be resurrected. Studies, as well as experience, have shown the importance of the demand side, if not necessarily a demand pull.

When measured with the help of indicators such as patents filed, Schmookler's classic study suggested that "inventive effort . . . usually varies directly with the output of the class of goods the inventive effort is intended to improve, with invention tending to lag slightly behind output" (Schmookler 1966: 118). His analysis has been refined, and for sectors such as chemicals and pharmaceuticals the opposite pattern has been found (Walsh 1984). His point has been

quoted extensively to argue that market demand forces govern the innovation process and that governments should therefore discontinue their traditional technology push policies. Ironically, now that some governments have been adding technology demand stimulation to their spectrum of policies, analysts are considering the dichotomy to be misleading, rather than helpful. "All that has really been established is that there was an adequate demand for those innovations which turned out to be successful. We agree, but how would we disagree?" (Mowery & Rosenberg 1979: 107).

The ideology of demand pull misleadingly assumes that technology is infinitely malleable by demand, whereas some constraints are imposed by nature and are a consideration in technology development projects. Furthermore, the needs and wants of people are manifold and may pull technology in different directions (see Vol. 1, Ch. 3). The general point about technical change is that users and consumers simultaneously need to learn not only how to handle a (new) technology once it is introduced but also to articulate demand.

Demand will be articulated in interaction with supply. When in the late nineteenth century, motors were installed on wagons so that they became automotive, no articulated demand for automobiles existed (Abernathy et al. 1983: 25–6):

Producers gradually learn to distinguish the relevant product attributes for which they must supply technical solutions acceptable to the market. . . . Taken together, these attributes constitute an industry's basis of competition—that is, they define the arena within which different producers stake out their distinctive positions.

Thus, researchers should speak of *coevolution* of supply (and technology behind the supply) and demand.

The process of coevolution can, and will, be modulated by actors (the rough agreements and networks, for example), and this also allows a productive role for governments. But processes of coevolution cannot be shifted at will in any desired direction. A certain *nonmalleability* characterizes technology, not because actors have insufficient power or resources to get what they want, but because technological developments have, in a sense, rules of their own: from the heuristics in search processes to the normal ways of doing things in a technological regime. These rules are outcomes of action and interaction, leading to the particular form that irreversibilities take in the situation of technical change in societies. Because such rules function at a collective level, they cannot be changed easily by any one actor.

In the economics of technology, nonmalleability is often argued in terms of what is happening within firms (and in relation to an evolving stock of technological knowledge) (Freeman & Soete 1990: 84):

... innovative activities are strongly *selective*, *finalized* in quite precise directions, and often *cumulative*. This concept of technology is very different from the equation of technology with information that is generally applicable and easy to reproduce and re-use, where firms can produce and use innovations mainly by dipping freely into a general "stock" or "pool" of technological knowledge. Instead, we have firms producing things in ways that are differentiated technically from things in other firms, and making innovations largely on the basis of in-house technology, but with some (and varying) contributions from other firms, and from public knowledge. Under such circumstances, the search processes of industrial firms are *not* likely to cover the whole stock of technological knowledge before making their technical choices.

The cumulateness of technology, here related to the dynamics at the supply side, is one aspect of nonmalleability of technology. The OECD (1992) recognizes three main aspects:

- *Cumulativeness of technical knowledge* Technological developments are always performed locally and thus cannot be moved without effort. Learning processes occur: learning by doing (e.g., increasing the efficiency of production) and learning by using. As a consequence, firms, institutions, or countries that have built up skills have a better position to adapt to new technological possibilities. Cantwell (1989) found a fair degree of stability within the group of world leaders; he attributed the stability to technological accumulation. Likewise, firms and countries lacking institutional learning (including many less industrialized countries) are disadvantaged.
- *Paradigms and trajectories* Patterns in technical change across firms are often carried by a community of technology actors (to broaden Constant's (1984) concept of a technological community). Such patterns have been called "technological regimes" (Nelson & Winter 1977), "technological guideposts" (Sahal 1981), and "technological paradigms" (Dosi 1984). A technological paradigm embodies a definition of the relevant problem and suggests directions for further inquiry. The patterns guide and channel the efforts and technical imagination of engineers and of the organization (firms, public laboratories, and other technology institutions). Similar guiding and channeling, but in a more diffuse way, occurs through regimes and macro-level patterns, variously called the "techno-economic paradigm" (Freeman & Perez 1988) or "régime de régulation" (Boyer 1988).
- *Increasing return to adoption* Often, in contrast to the conventional view, technology is not chosen because it is efficient, but it becomes efficient

because it has been chosen. One explanation of increasing rates of adoption is that, the more a technology spreads, the more is learned about its use, the more it improves, and the more it is likely to be adopted by subsequent users. This is one of the positive-feedback mechanisms that Arthur (1988, 1989) used to argue that the path followed in its introduction and early adoption defines the learning and further development of the technology (e.g., the internal combustion engine). If another path had been followed, another technology would have emerged (e.g., electrical or steam power). Thus, technological development is path dependent.

Path dependencies refer to the interrelatedness of artifacts with other artifacts, infrastructure, and routines. New artifacts have to change or even undo these linkages, and this will meet with resistance. If governments or societies desire a new technology, they must not only construct its artifacts but also create a transition path toward it.

#### *Theories to explain technological change*

To understand and explain technical change, a combination of economic and sociological theory is necessary. We shall focus on a few recent and fruitful theories, which have the additional advantage of being relevant for the question of orienting technology. They contrast sharply with traditional economic theories.

Mainstream economics tends to treat technology as an exogenous variable, which does not have to be studied itself. When technological change is included in economic analysis, it is treated abstractly. Technical change may be treated as a shorthand for any kind of shift in the production function. In other words, if economic growth cannot be explained by other economic variables, it is, by definition, the result of technical change. At the macro-level, technical progress then appears as the so-called residual: whatever is left to explain economic growth in a regression equation, after the effects of labor and capital have been accounted for (Vol. 3, Ch. 1).

Within mainstream economics there have been two attempts to endogenize technical change: the theory of *induced innovation* since the 1960s (Kamien & Schwartz 1968, Binswanger 1974) and *new growth theory* since the 1980s. In induced innovation models, technical change is assumed to respond to changes in relative prices and thus be directed toward economizing the use of a factor which has become relatively expensive. Researchers model nonmalleability by representing technological opportunities as an innovation possibility function (or frontier), with specified attainable rates of factor augmentation (Stoneman 1983). In endogenous growth models, technical change derives from research (leading to designs, blueprints, and general knowledge) and human capital accumulation, and is modeled as a stock variable, with spillovers to other factors of production (and in some models, also to research) (Romer 1986, Lucas 1988;

for surveys, Verspagen 1992, Schneider & Ziesemer 1995). Compared with the features of technical change discussed in the preceding subsections, these models only explain incentives for firms to do research under different conditions.

Nelson & Winter (1982) and other evolutionary economists have struck out in a different direction to endogenize technical change. Their theories are an alternative to neoclassical economics (see Dosi et al. 1988). Nelson & Winter developed a dynamic picture of firms and an evolutionary theory of economic change in which an evolutionary theory of technical change was embedded. Thus, they combine the focus on firms with a perspective on technology.

The starting point of the theory is uncertainty (Nelson & Winter 1977). Firms do not know beforehand which technology will be successful; they even lack the possibility to check all technological alternatives and, as a result, their behavior should not be understood as maximizing. Instead, firms have *heuristic search routines* to which they hold for while. These routines produce new findings, blueprints, or artifacts that should be viewed as variations, similar to biological mutations, which may succeed or not in a *selection environment*. The selection environment includes the market, but also institutional structures as, for example, the patent system.

In later studies, the further point (already noted in the previous subsection) was made that, even within firms, search processes are also informed by technological paradigms (Dosi 1982), or technological guideposts (Sahal 1981), which are available at the level of the sector or of technological communities. This indicates that sociological explanations have to be added to the economic theories.

Sociological explanations include two types: quasi-evolutionary theories, following Nelson & Winter, take search processes as a starting point; and sociotechnical theories focus on configurations that work. These are mutually compatible and also appear to complement, rather than contradict, evolutionary economic theories.

In the quasi-evolutionary approach (Van den Belt & Rip 1987, Rip 1992, Schot 1992), heuristic search practices leading to technological options, artifacts, or transferable skills (embodied knowledge) relate to shared repertoires embedded in an organization, in a community of technical practitioners, or in an inter-organizational network. The variation is not random, but guided by heuristics and by other promises of success. The selection environment is actively modified to increase the survival chances of a search product. One form of this is the creation of a niche or protected space, in which the product can survive more easily—for the time being. Coupling between variation and selection can become institutionalized in a *nexus*; test labs in the dyestuff industry (Van den Belt & Rip 1987), are one example; environmental staff and departments in large firms (Schot 1992) are another. The coevolution processes are channeled

by such a nexus. Alliances and networks can play a similar role, when rules of the regime emerge, which modify search and technological development decisions. International consortia in microelectronics and some of the R&D stimulation programs of the European Union appear to link variation and selection in such a way.

In sociotechnical theories, the building, maintaining, and expanding of configurations that work is the starting point of the analysis, with due recognition of the necessary complementary configuring of the environment. Hughes (1983, 1987), especially in his study of electric power networks (networks here in the sense of linked artifacts), has shown how network builders bring together social as well as technical elements in order to make the environment part of the system. An interesting finding is that the dedicated network (or system) builders are different in different phases: inventor-entrepreneurs, engineer-entrepreneurs, and financier-entrepreneurs. In parallel, an inherent logic of the system develops, with a momentum, a drive toward expansion (e.g., because of load factor requirements), and the need to overcome obstacles in the expansion.

The sociotechnical approach has been used to address contemporary issues of large technical systems (Mayntz & Hughes 1988) and to understand telecommunication networks (e.g., Schmid & Werle 1992). Stankiewicz (1992) argues that a qualitative change occurred in the 1980s from technology as local concrete systems to technology as a global sociocognitive system in itself. Technological activity is increasingly self-referential; the list of priorities is more and more derived from the needs of the global system than from the local systems.

A similar interest in sociotechnical dynamics of heterogeneous actors, that is, without a limitation to firms, is visible in so-called actor-network theory. Case studies focus on the interactions between the actors and evolving technoeconomic networks (for case studies, see Callon 1986a,b, Law 1987, Law & Callon 1988, Mangematin & Callon 1995, Latour 1996). Recently, the approach has been used to develop instruments for strategic analysis and policymaking (Callon et al. 1992; see also OECD 1992).

The advantage of the evolutionary, quasi-evolutionary, and sociotechnical explanations is that, in contrast to the neoclassical explanation, they also cover public technologies and the increasingly important public and private settings of technical change. Sociotechnical theories are especially flexible, because the context within which novelty creation occurs is not specified beforehand. This flexibility is also a disadvantage, however. Without any specific theoretical structure, researchers fall back on case studies, and, as it turns out, on heroic storylines, where novelty is attempted against overwhelming odds. In evolutionary and quasi-evolutionary theories, no such storyline can be followed.

*Complex trajectories of technology*

Dynamics and outcomes cannot be separated. The emergence of irreversibilities and the relative nonmalleability of technology are outcomes, but at each moment they are also slices of dynamics. However, managing technology requires an understanding of the relation between actions (induced dynamics) and their outcomes. A theory of prospective technology dynamics is needed, even if the contingencies involved reduce any hope of arriving at determinants or factors of successful direction.

To arrive at such a theory is methodologically complex because of the retrospective bias involved in using history to explain the present. Historians have highlighted the shifts in actual developments. Sociologists and political scientists have pointed at factors modifying or overriding immediate economic considerations. Explanations are often glosses on particular case studies or depend heavily on the particular cross-section taken through a multilayered backdrop (Fig. 6.2). The literature cannot yet support a systematic presentation of prospective technology dynamics. We therefore limit ourselves to vignettes that highlight important elements.

We first discuss the complexities of studying outcomes and some of the explanatory glosses available in the literature. There is no meteorology to map the winds of creative destruction (Abernathy & Clark 1985), but it is helpful to distinguish between relatively *stable design hierarchies* (Clark 1985) and *hierarchies in flux*. Using this distinction, we briefly discuss two issues: mapping technical trajectories and the issue of radical innovation.

*Complexities of explaining outcomes of technical developments*

Linear technological development, that is, development along a dimension of presently dominant functionality, cannot be assumed. If it occurs at all, it is a particular type of development and one that needs to be explained itself. A better metaphor is the way yeast cells grow, with developments branching off in different directions, and cross-connections and interactions complicating the picture further.

Implicit in this metaphor is the idea of *niches*, not in the specific sense of market niches, but like evolutionary niches in biology: limited and relatively easy and/or advantageous domains of application and further development that strongly determine what steps can be taken productively. Instead of niches, analysts could also speak of protected spaces, linked to wider environments (Law & Callon 1988).

Marvin and Nye demonstrated that spectacular lighting rather than domestic lighting (now often seen as an important part of electrification) was a main route along which the technology was introduced and developed further (Marvin 1988, Nye 1990; see also Hughes 1983). The other important route was

local transportation (trams, trolley buses) and the amusement parks to which they gave access. By 1900, the penetration of electricity in local transportation was 80–90 percent, but for domestic electric lighting 3 percent, and for electric motors less than 5 percent (in total horsepower used in industry). The direction of technological development was determined by the actual paths and the expectations of what could be next steps along these two main routes. Our retrospective idea of steps in the direction of the situation as we know it is irrelevant. Marvin draws out a methodological moral (Marvin 1988: 154):

That we no longer remember the excitement of electric light spectacles testifies both to the fact that [electrification since the late 19th and early 20th century has taken other turns] and to the tendency of every age to read history backward from the present. We often see it as the process by which our ancestors looked for and gradually discovered us, rather than as a succession of distinct social visions, each with its own integrity and concerns. Assuming that the story could only conclude with ourselves, we have banished from collective memory the variety of options a previous age saw spread before it in the pursuit of its fondest dreams.

The nature of niches and their dynamic is not limited to economic aspects; meanings attached to an artifact can play a dominant role. So long as dominant social groups saw the large frontwheel bicycles of the 1860s and 1870s as interesting and challenging, and safer alternatives as irrelevant, no one had an incentive to develop the safety bicycle (Bijker 1995). In such niche-based, branched developments, the eventual shape of a technology, its use, and the way it is embedded in society can be very different after five, ten, or more years from its form at the beginning.

For this reason, in the new history and sociology of technology, conceptual and methodological issues, rather than explanation, have taken precedence (see Bijker et al. 1987). In describing the development of artifacts, for example, impartiality with regard to successful and unsuccessful developments is necessary; otherwise, analysts end up with a distorted linear picture of what has happened. In the *social construction of technology* approach (Pinch & Bijker 1987), variety is related to different social groups having different problem definitions, different interpretations, and hence different solutions. Success is explained as closure, that is, a dominant interpretation arises, which becomes identified as the artifact—*the safety bicycle* becomes *the bicycle*.

The new history and sociology of technology has shed light on forgotten views and failed technological directions, but it has not progressed very far in the direction of theory. One possibility is to explicitly reconstruct agenda building and strategies of inclusion or exclusion as the mechanisms of closure, as well



as the breaking up of closure (Bijker & Law 1992). In such a theory, power appears as the outcome of interactions, and is sedimented in technical configurations, rather than somehow given beforehand. In Albert de la Bruhèze's (1992) study of the political construction of technology, in the case of radioactive waste-handling technology in the United States, this point is very visible, with the Atomic Energy Commission's partly unintended creation of a radioactive waste domain in which it was dominant.

An explicit explanatory approach is taken in labor process analysis (Braverman 1974), politics of technology (Winner 1977), and interest-and-control theories (Noble 1984). This approach starts with a general sociopolitical theory and argues that technologies are shaped within the context of power struggles and hence reflect and reinforce the unequal division of power and control. "The issues that divide or unite people in society are settled not only in institutions and practices of politics proper, but also, and less obviously, in tangible arrangements of steel and concrete, wires and transistors, nuts and bolts" (Winner 1986: 29).

This, clearly, is an important point. Winner's best known example is the extraordinarily low bridges over the parkways on Long Island, which in the 1930s "were deliberately designed and built that way by someone who wanted to achieve a particular social effect" (Winner 1986: 23). The goal of the designer, Robert Moses, had been to limit access of racial minorities and low-income groups to Jones Beach. They had to travel in buses, which could not pass under the low bridges. (By now, the original social effect is less pronounced, but the bridges are part of the sociotechnical landscape.) Noble (1984) has shown how the choice of a design of automated machine tool systems was part of the struggle between management and labor.

This type of explanation assumes malleability of technology: given enough money, or another form of power, the technology reflecting the interest of the powerful actor will emerge. The moral is then to become powerful, rather than to understand the dynamics of technological development. In fact, these dynamics are sometimes black boxed: the similarity or affinity of the outcome with the interest of the (supposedly) powerful actors is taken as a sufficient explanation of what happened.

At this stage, explanations of the eventual shape of technology tend to be glosses on specific case studies, informed by general sociological theories. Much more than this may not be possible, given the complexities of technological development and its coevolution with societal developments. A more limited goal may be achievable, however.

Even with these complexities, distinguishing between relatively stable and unstable situations permits the formulation of realistic objectives. In unstable situations, researchers may not be able to explain or predict what will happen;

instead, they can study the conditions for what, in retrospect, is called radical innovation. For the question of guiding technological development in desired directions—which may require radical sociotechnical innovation—such a limited objective may be sufficient.

The general perspective of novelty and emerging irreversibility has been specified by Clark (1985) with the help of the notion of a *design hierarchy*. After an initial period, an overall concept or definition of an artifact or product stabilizes. Changes occur, but at lower levels of the design hierarchy, for example, by improving components. In such a situation, mapping of change in performance is relatively easy, because the dimensions of performance are articulated and stable. When the design hierarchy shifts or loosens up completely (because of new technical possibilities, new user possibilities, competition with alternatives), analysts can map the type of change (for example, whether existing competencies or existing technical and market linkages are disrupted) and changes in performance on those dimensions that are central to this change.

Broadening Clark's concept leads to a sociotechnical hierarchy, describing the stabilized design, operation, and use concepts of a technical system or a regime. Design hierarchies (e.g., of a type of motorcar) now appear as parts of the sociotechnical hierarchy, for example, of the internal combustion engine/motorcar/transport and mobility regime.

For stable hierarchies, more or less simple mapping exercises can be enough to indicate the future shape of technology. For hierarchies in flux—or no hierarchies at all—prediction on the basis of internal characteristics is impossible. As a proxy measure, analysts can look at sources of novelty and conditions of change. In the end, historical and sociological analysis should prevail to trace and explain formative moments, critical junctures, and the reasons for the emergence of periods of relative stability where standard operating procedures dominate.

#### *Mapping simple trajectories*

The main motivations for mapping techniques have been the need of policymakers to assess the present and future state of technologies (and sectors) and the need of firms and technology organizations to forecast developments (in technology, but actually also in markets or even in society). We shall briefly discuss some techniques and approaches that have been developed.

Various kinds of monitoring techniques are used, often drawing on technical intelligence and expert judgment (see Schaeffer 1994 for an overview). A widely used approach is to distinguish among technologies described as advanced (or frontier), state-of-the-art (or best practice), off-the-shelf (or average practice) and older (obsolete), and to map which kind of technology is present where (Clark & Wheelwright 1993). The *technometrics method* that has been developed

by the Fraunhofer-Institut für Systemtechnik und Innovationsforschung (Grupp et al. 1987) can be seen as a further refinement: it uses technological indicators (of performance and of relative performance compared with other countries or firms) to create a profile of a country or a firm that can be compared with other countries or firms. In both cases, experts provide aggregated evaluations of technology, which may be detailed as locations in morphological analysis (Foray & Grübler 1990) or a tree diagram (Durand 1990). The problem remains that the actual routing through the tree can be traced only after the fact. In addition, with novel technology, new dimensions of the phase space of possible developments may emerge. In other words, such approaches work better when a stable sociotechnical hierarchy can be assumed. The complexities of the situation have occasionally been recognized and discussed (e.g., Sigurdson 1990).

A further step is to use mathematical and statistical techniques to extend quantitative time-series data into the future. Again, the assumption is that the technical attributes change in an orderly and predictable manner. Most trends are not linear over time, but exponential or S-shaped. Envelope curves constructed by stacking S-shaped curves, one after and over another, can form a linear or exponential trend. The explanation of S-shaped developments is that progress in developing a technology starts slowly as many impediments must initially be overcome, advances rapidly for a period, and then slows as the easy improvements have been mined. It is a learning curve; see Young (1993) for an overview. Given the branched character of technological development and the detours that occur, the use of diffusion curves (or, in more advanced models, Markov chains) has to be justified explicitly.

An approach, inspired by the ecological sciences, is to use Lotka–Volterra equations, which model how species in ecotopes vary in numbers over time. In the case of technology, in a *technotope* (a part of the market, or a niche) technologies and products interact with each other, resulting in their respective market penetration. In forecasting the market share of various energy carriers, basing model specification on data from a 20-year period (1900–1920), Marchetti & Nakicenovic (1979) showed that the equations provide good fits with historical developments.

Lotka–Volterra equations provide a general approach to trend analysis. They are also the starting point of recent sophisticated modeling of nonlinear and self-organization processes that attempt to capture features of technological development (Allen 1994). But fitting data to find a value for the relevant parameters by nonlinear multiple regression becomes more and more difficult as the number of competing technologies increases. A principal issue is that only competing technologies at the same level can be modeled. Thus, a Toyota and a Ford compete with each other, but cars as a system compete, for example, with railway systems. And the transportation and mobility system of which they are

part has its own growth pattern in relation to other sociotechnical systems. For overall patterns, a qualitative analysis based on the multilayered conceptualization of Figure 6.1 is necessary. In such broader approaches, technology as the material landscape of society, technology in everyday life, and what has been called the domestication of technology (Sørensen & Berg 1991) have to be included as important parts of the dynamic, not just as impacts after the fact.

#### *Radical innovations*

For prospective technology dynamics, radical innovations are a problem: by definition, they are considered to be unpredictable. But research may go one step back and inquire into the *conditions* for radical innovation. Sources of such innovations are probably less interesting than the conditions of challenge and overthrow. Despite the association with heroism in this terminology, such conditions may often derive more from circumstances than from special innovative effort.

Many so-called technological breakthroughs were achieved in wartime, when demand for new and better military technology is especially high, regardless of cost, and there is a need to develop substitute products and materials when nations are cut off from critical supplies. The technological variety on which to build was often already available and is sometimes developed in niches (e.g., polymeric materials before the Second World War), but a different kind of selection environment was necessary. Wilkinson (1973) has generalized this idea in arguing that the driving force is not the expectation of progress, but poverty, that is, stressful circumstances that force actors, against their inclination, to look for solutions.

These observations are important to understand the limitations of the often-heard statement that radical innovations depend on new scientific insights opening up new technological and economic opportunities. For example, Maxwell's theory of electromagnetism in the 1860s was instrumental, through Hertz's further work, to the development of radio technology. Understanding the phenomenon of electromagnetism did not lead directly to the radio as a new consumer product; several decades of applied research and experimentation were needed to turn it into a tradeable product. Although scientific findings opening up new areas were necessary for this radical innovation, they were not sufficient. *Science push* is not a complete explanation. *Demand pull*, on the other hand, is not sufficient either: in the examples of wartime need, a reservoir of scientific findings already existed to build upon. It was their mobilization and recombination that allowed the radical innovation.

Another element in (radical) innovation is advances in engineering and material technology. James Watt's steam engine, with its separate condensing chamber, depended for its production and its success on Wilkinson's boring

mill. This is a case where the complementary technology led. Innovations which are radical for a regime may themselves have been constructed out of incremental use of various complementary technologies; the Sony Walkman is one example.

Although the radical character of an innovation is an outcome of its development and its success, elements at an early stage help shape its radical character, or act as favorable conditions. The perception of a pressing technical or market-derived technical problem that apparently cannot be met with available technologies sets in motion a search for different solutions. Such problems may be related to bottlenecks or obstacles arising in the growth of technological systems or derive from pervasive shifts in consumer preferences, for example, interest in environmentally friendly technologies.

Sometimes, existing trajectories reach certain technical limits, or further advances along the same trajectory run into increasing marginal costs (Saviotti & Metcalfe 1984). This situation could be an anomaly with respect to the existing paradigm, which will continue along normal lines, but it may also be a *presumptive anomaly*, which drives the search for better solutions, especially if there is a promising alternative to be developed (Van Lente 1993). Constant (1980), who introduced the concept of presumptive anomaly, has shown it at work in the late 1920s, when insights from aerodynamics indicated that the conventional piston-driven propeller could not provide the near-sonic speeds foreseen for airplanes. To solve this problem of the future, the turbojet engine was developed—which eventually led to a new propulsion system.

Institutional factors are important favorable conditions. In particular, innovation is fostered by an outsider position which allows risk taking. Insiders have less leeway with risk taking than outsiders; community practice may define a cognitive universe that inhibits recognition of a radical alternative to conventional practice (Constant 1984). This is a matter of vested interests, whether it is a technical community, a large organization, or an established technical regime. Some distance has to be created.

The argument applies also to firms and organizations of the late twentieth century. Radical inventions may endanger current activities of firms and, for that reason, they may be rejected or delayed, even amid a general recognition that technological competition is important for the survival of the firm (Hughes 1987: 59):

Radical inventions often deskill workers, engineers, and managers, wipe out financial investments, and generally stimulate anxiety in large organizations. Large organizations sometimes reject the inventive proposals of the radicals as technically crude and economically risky, but in so doing they are simply acknowledging the character of the new and radical.

The importance of the propensity to take risk and of entrepreneurship in creating novelty lies in changing the strategic games in which firms and sectors are involved, not in the market share achieved, for that is likely to be small (at least in the early years). By championing a radical innovation, other firms are induced to change their strategies. In modern biotechnology such a dynamic is clearly visible. Strategic games are an important element in the development of radical innovation. The development of clean coal-burning technologies is strongly supported by the coal industry in an attempt to secure coal usage in a world where environmental regulation is tightening. Electricity producers have supported the development of the electric car, as have producers of plastics. Customer firms may also actively support the development of new technologies, by providing information about product requirements and their involvement in tests. Even consumer groups may be involved directly in the development and support of new technologies. When firms take such anticipatory actions, they are responding to a problem of the future (a presumptive anomaly) in terms of a threat to the strategic position of the organization.

The cumulative effect of these dynamics is important for developing alternative technological trajectories, to give them sufficient momentum. When firms possessing great market power, specialized knowledge and larger financial assets commit themselves to the development of such a trajectory, a threshold may be passed. Secondly, through the commitment of other firms, a dynamic learning process can emerge, resulting in a wide array of postinnovation product improvements, complementary innovations, and cost reductions, all of which give the new regime enough momentum to replace the old one. The advent of the personal computer can be described in this way.

The roles of universities and public laboratories in the generation of the original innovations, as well as government procurement in their early development (e.g., in integrated circuits and electronic networks), clearly show that radical innovations often cannot be sustained by traditional market mechanisms and firm strategies. If innovations are to replace or at least fundamentally modify existing paradigms and regimes, institutional and regulatory changes must take place in each country. Freeman (1992) uses the emergence of what he calls "the new technoeconomic paradigm" of information and communication technology (i.e., their pervasive effects in society) as an argument for this point; public programs for computer technology and public policies for the telecommunications infrastructure were essential steps.

Clearly, the issue of radical innovation leads to consideration of the dynamics of changes in paradigms and regimes. Only through such eventual changes can an innovation actually turn out to be radical.

*Coevolution in sociotechnical transformations*

The notion of coevolution, derived from a consideration of the dynamics of technical change, applies to sociotechnical transformations as well as to individual technologies, even if the concept cannot then be used in the strict sense (because there are no separate streams that coevolve). What coevolution continues to indicate, now at the level of regimes and sociotechnical transformations, is that overall changes result from several interacting developments together, rather than from a point source of change forcing itself upon the rest of the world. The discussion of radical innovations in the preceding subsection supports this general point.

This implies also that researchers cannot simply speak of the impacts of a technology, not even of a technological project. Impact analysis has been done extensively over the past two or three decades, and when the project for which impacts are to be studied (e.g., in an environmental impact assessment) is well defined, a reasonable (but project-specific) job can be done (Hildebrand & Cannon 1992). Technology assessment has been concerned with versions of impact assessment of specific technologies and, because their starting point is more diffuse (a new technology), their results are necessarily more speculative. However, the key problem is that impacts are *co-produced* by the several actors involved. So, any impact assessment depends on the nature, and the traceability, of the co-production processes. For this reason, technology assessment, especially in Europe, has evolved from a policy analysis tool into support for dialogue and interaction among the actors actually and potentially involved in co-production processes.

Technology is often seen as a causal force: a source of strategic advantage, wealth, and quality of life, and developed, stimulated, praised (and blamed) for that reason. But is it, by itself, such a source? Again, the situation is more complex. Not only is the idea of a source as such too limited, but the causality is not clear—in spite of widespread beliefs about causal relationships.

For example, technology innovation may offer competitive advantages to a particular firm, but definite risks as well (Teece 1986). It may not lead to overall wealth creation, especially not in the short run. For information technology, heralded as certain to improve efficiency and productivity, the absence of these demonstrable improvements has created a puzzle, a paradox if coupled with the conviction of wealth creation through technology.

Another example can be found in the complex relationship among medical technologies (in a broad sense, including drugs) and decrease in mortality, improved health, and possibly also improved well-being. The dramatic reduction in mortality between the late nineteenth century and the middle of the twentieth century owes more to public health measures, increased hygiene,

and better conditions of life in general, than to advances in medical science (McKeown 1988). Present-day medical technology is torn by pressures to come up with miracle cures, financial restrictions, and criticism of at least some of its outcomes as having negative effects on well-being.

Although decisionmakers' beliefs in direct causal linkages may be unfounded, so long as such beliefs guide their strategies and actions, these decisionmakers will work toward the desired outcomes (wealth, health, and so on), and sometimes their efforts will result in such outcomes. Regularities are an effect of actor's strategies and interactions, rather than something given beforehand.

Clearly, a full account requires a broad analysis in which technology (in its different senses) is one component among others. Here we focus on structures and institutions as intermediaries between dynamics of technical change and overall sociotechnical transformations. This is an important part of the puzzle for our question of managing technological development and the attendant interest in technological regimes.

We briefly indicate aspects of coevolution at the level of sectors and economies, and discuss more extensively the strongly asymmetric coevolution patterns in less industrialized countries. In the latter case, we are also interested in opportunities for change, including change to more environmentally friendly technologies and sociotechnical landscapes.

#### *Coevolution of technology and sector and global structures*

Economists, following Schumpeter (1934), have studied the effects of concentration in an industry and, to some extent also the effects of size of firms, on innovation. Schumpeter's thesis that both market power and the size of firms work to increase innovative activity is not borne out by empirical data (Kamien & Schwartz 1982).

Causality works in both directions. Industry structures influence propensities to innovate, and condition differential success of innovations. But firms' strategies and their outcomes also shape and reshape industry structures. Feedback loops have to be added to the structure–behavior–performance paradigm in industrial economics (Bain 1959). Such an extended theory has been formulated (without reference to industrial structures) by the sociologist Boudon (1981), who distinguishes different dynamics depending on the extent of the feedback loops: from reproduction of existing structures to overall transformations.

The collective dynamics of technology introduce further complexity to the structure–behavior–performance paradigm. Historians and economists have identified such dynamics in retrospect, for example, the shift from economies of scale to economies of scope as the joint outcome of industrial and techno-



logical developments (Chandler 1990). In another vein, Hughes (1989) analyzed what he called the tidal wave of technological ingenuity and enthusiasm in the United States; this created a particular form of modernity (with hierarchical control orientation and tightly coupled systems) that is inappropriate to the present-day world and is being changed partly through technological developments in the direction of distributed systems.

Freeman (e.g., Freeman & Perez 1988, Freeman 1992) introduced the notion of a technoeconomic paradigm to capture the effect of what he calls a pervasive technology, that is, a technology that not only changes its own sector but also the whole economy because of the pervasive effects in many sectors. Steam power, coupled with iron and steel, arguably constituted the technoeconomic paradigm of the railway (and steamship) age. Although such a paradigm is dominant, technologies (in this case, electricity) develop that will characterize a subsequent paradigm. In retrospect, analysts can speak of a mismatch of the new technologies and the socio-institutional context shaped by the dominant technoeconomic paradigm (Perez 1983). For the present period, Freeman sees the new information and communication technologies as the emerging technoeconomic paradigm of the 1990s and later decades. This is not so much a question of wealth creation (compare the productivity paradox) but of changing structures and interactions. One example would be the new possibilities for co-production when information exchange is not limited by geographical distance.

Globalization—the phenomenon of firms taking the whole world as their arena (so that the concept of comparative advantage is put into practice)—has been linked to new technology. OECD (1992) emphasized the combination of global competition, world oligopoly, and new forms of cooperation, and argued that “contemporary technology lies at the root of the process, acting as an enabling factor and exerting pressure towards further globalization” (OECD 1992: 211). World oligopolies are not new; they have long existed, for example, in oil and metal industries. What is new is that they “now constitute the dominant form of supply structure in most R&D intensive or ‘high-technology’ industries, in many scale-intensive manufacturing industries, and service industries” (OECD 1992: 222).

The coevolution of technologies and industry structures is important for the issue of global climate change because of the reduction in energy and materials requirements, especially in industrialized countries in which the material needs are largely saturated and more advanced, energy-efficiency technologies are used. The industrial metabolism of our society is changing (Grübler 1994: 56):

Industry has built in an *inherent incentive structure* to minimize factor inputs. This is primarily driven by economics and by continuous technological change. Therefore, industry moves in the right direction, and the

real issue is how to accelerate this desirable trend . . . [toward] *dematerialization* . . . and . . . *decarbonization*.

Even without Grübler's optimism, the general point is clear: tracing the patterns of coevolution and understanding their dynamics is important, so as to help them along a little, and in the right direction. It is difficult to do more than diagnosis, but as Grübler (1994) and Freeman & Perez (1988) exemplified, each in a different way, it should be a historically informed diagnosis.

*Sociotechnical transformations and less industrialized countries*

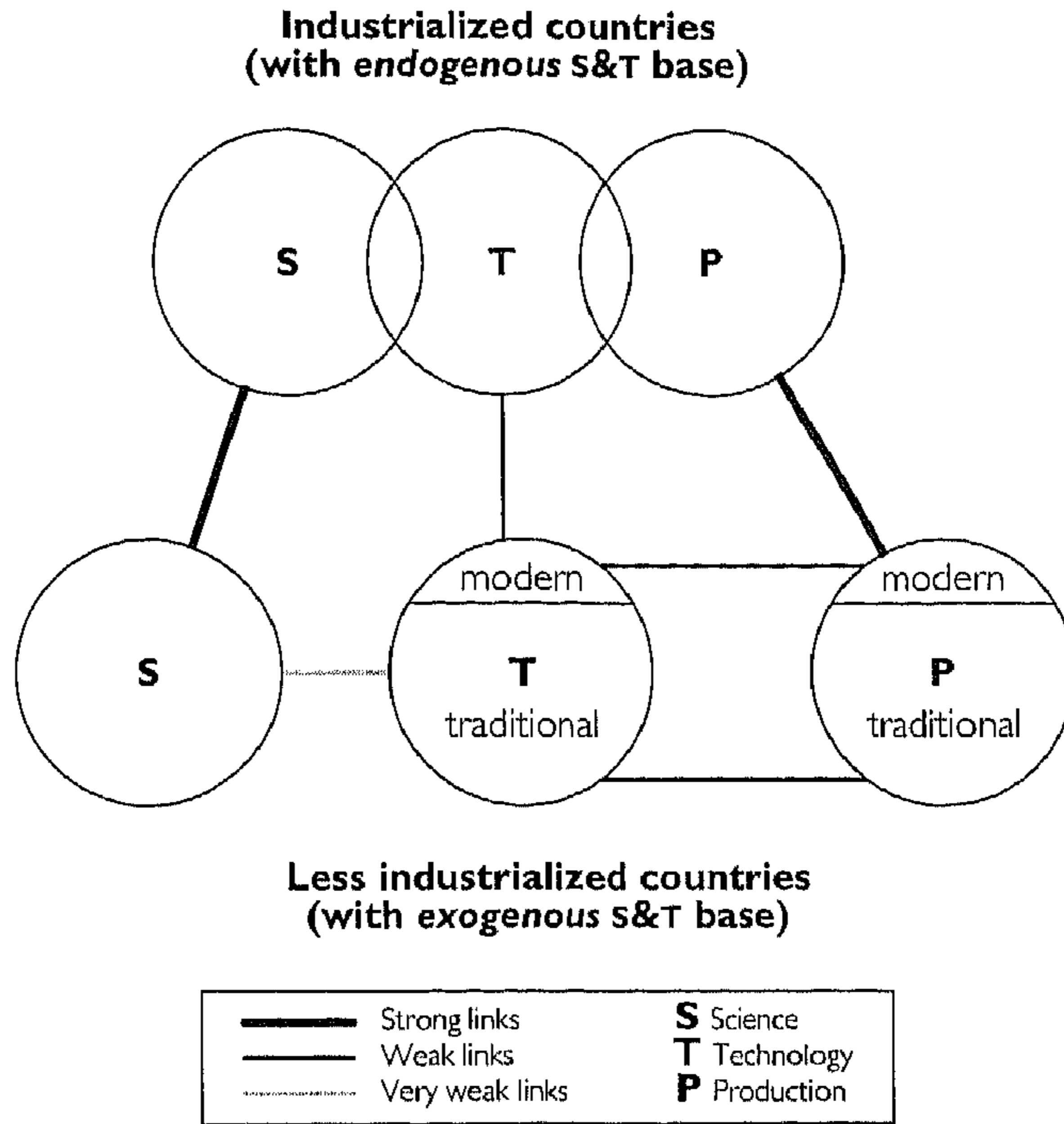
The less privileged position of less industrialized countries in the global system raises the question whether they can change their position in the system at all, in addition to the difficulties of changing their own particular economic regimes for the better.

In abstract economic models, the low wage rates of less industrialized countries will in the long run compensate for their lack of innovative capacity and eventually reverse the international trade and income flows. However, this process occurs only if less industrialized countries are able to produce the newest technologies by themselves after a certain period. In other words, the capacity to learn is a prerequisite for these countries to escape from the vicious circle of repetitive technological imports. For this reason most modern technology-gap models focus on the crucial time element between innovation and imitation abroad as the trade and income-polarizing reversal factor.

In the so-called product lifecycle theory, a division of labor is envisaged which has indeed occurred for traditional sectors such as the textile industry. In a first stage, investments are large and performance is what counts. The locus of production is in the North. When competitors arrive on the scene and mass production allows economies of scale, other factors become important, including proximity to markets. In a third stage, the industry is mature and can be localized almost anywhere. Unskilled labor can still do the job, and low wages in less industrialized countries attract the industry.

One problem of this type of theory is that it views less industrialized countries as empty receptacles, characterized only by abstract features such as low wage rates. But these countries have trajectories of their own, and technology is involved in them in various ways. A basic point has been made by dependency theories, which look at less industrialized countries as depending on developments in the dominant center of an asymmetric global system (see Vol. 1, Ch. 5).

Sagasti (1978; see also Salomon et al. 1994) has visualized the several dependencies between the science and technology bases of industrialized and less industrialized countries as in Figure 6.2. These dependencies are often read as



**Figure 6.2** Different kinds of dependencies between the science, technology, and production bases of industrialized and less industrialized countries.

less industrialized countries being victims of consciously or unconsciously imperialistic industrialized countries, but all countries are in fact caught in this structure.

The structural constraints on the science and technology base (or national system of innovation) of less industrialized countries are part of the dependency story. Technological developments, creating novelty, may create opportunities for newcomers. Perez & Soete (1988) argue that thresholds are temporarily low when paradigms change, and windows of opportunity may open for new participants. Perreira (1994), following Perez, considers times of paradigm change as offering a double technological opportunity: to exploit certain components of the old paradigm, and to get into the new paradigm at an early stage.

Perez & Soete (1988) recognize that the process of catching up is extremely difficult for less industrialized countries, especially for the production of capital goods. These countries will have a chance to catch up only if the technological leaders are locked into the earlier paradigm and do not move quickly. Then, less industrialized countries may be able to move more quickly. Will their govern-

ments be able to compensate for the lack of locational and infrastructural advantages? Can dynamic entrepreneurship take up the challenge? Or is it exactly such entrepreneurship which is suppressed by the structure of the national and international economy?

Nevertheless, some less industrialized countries have crossed a threshold. A crucial point is the institutional capacity to learn: not so much the ability to develop the endogenous science and technology base, however important that may be, but the ability to scan the environment and to adapt systems of production and innovation to changing circumstances.

Information and communication technologies allow globalization, but may also increase the gap between industrialized countries and their companies, and less industrialized countries. Industrialized systems can appropriate the advantages of greater complementary assets in their production and distribution structures (Salomon et al. 1994). Biotechnology may offer greater promise to less industrialized countries, because it does not require large infrastructures, and it can be applied at different levels of complexity, investment, and effort (Pereira 1994).

Another type of question is about the prospects and opportunities for less industrialized countries to reduce greenhouse gas emissions or adapt to climate change. Does the fact that these countries are locked into the hydrocarbon regime to a lesser extent than industrialized countries provide them with an opportunity to grow in a more environmentally benign way? This question has not been studied in a systematic way. However, case studies on technical change in less industrialized countries, especially in relation to energy, suggest that there are many technological, economic, and socio-institutional barriers to such technical leapfrogging (Jhirad 1990, Abdalla 1994). The conditions for a complex technology to function well are often difficult to create in less industrialized countries, where many imported technologies have fallen into obsolescence or perform badly. The capacity utilization rate of power plants in India is a little above 50 percent, despite energy shortages.

Such poor performance is not just the outcome of external factors such as a lack of spare parts, foreign exchange, or financial resources. Institutional and human constraints affecting the organization often lie at the root of the problem (Jhirad 1990: 379). These constraints affect both the selection and retention of management and staff, training, the use of new management schemes, improvements in accounting methods and planning practices, and incentives for efficiency at different levels.

If either the technology or the environment is unfitting, technology assistance programs are bound to fail. This held true for the technology assistance programs for renewable energy technologies. Foley (1992) wrote that the success ratio in renewable energy projects over the previous 15 years was low,

ny renewable energy projects did not work, and, of those that worked, few survived the departure of foreign project staff who installed them; the degree of spontaneous local replication was minimal. The Chinese biogas program, which involved the building of 7 million digesters, was an exception, probably because it was based on a longstanding tradition of fermenting sewage and animal dung.

The lessons from all this are that either the technologies should be made compatible with the existing institutional environment or that the institutional setting should be geared toward the use of the technology. The first strategy requires indigenous technological capabilities, a willingness to experiment with a new technology on the part of users, and the creation of technology alliances among research institutes, businesses, and utilities; the second requires removal of institutional barriers and provision of appropriate incentives (e.g., the removal of energy subsidies). Jhirad (1990: 366) talked about "the need for innovation on all fronts. Neither policy reform, nor managerial improvement, nor technological innovation, nor financial innovation alone can solve the problem of increasing the per capita delivery of electricity services tenfold under capital and environmental constraints."

Applying the evolutionary approach to technological change (see p. 355) to development issues blends classical and development theory. On the one hand, with regard to the external factors, it shares with the classical theory the conviction that linking up with the global (technical) market is an essential condition for economic growth (i.e., to catch up). On the other hand, with regard to internal factors, it shares with development theory the conviction that the main instrument for growth is competitive, and not comparative, advantage. Concerning the internal factors for growth, the evolutionary approach seems to underestimate the strength of the national systems of production and innovation in less industrialized countries. Furthermore, it largely neglects the structural and socioeconomic dependency relations between highly industrialized and less industrialized countries. Perhaps no country outside the limited group of newly industrializing countries can take advantage of the present windows of opportunity.

### *Conclusion*

A general theory of prospective technology dynamics has appeared. Researchers recognize irreversibilities and path dependencies. One question then is how to increase the chances for better path dependencies. Another question is how to identify and realize transition paths from the present situation to a more desirable one.

We now turn to considering the productive management of technical change. We must take into account that firms are not the only actors in technical change and that the carriers of technical change evolve, with hybrid networks and consortia becoming important. However, entrepreneurship will remain important.

### *Proactive management of technological change*

The idea that technology may be guided toward social and economic needs and goals assumes that an unambiguous set of societal goals can be enunciated. In reality, societies incorporate and express many different (sometimes contradictory) goals, the importance of which may change over time and will differ among people (see Vol. 1, Ch. 3). But even if individuals, communities, and society as a whole can be clear about a goal, how could technology be oriented toward this goal? This is the problem of control. Earlier we saw that technological developments and their impacts are multiactor, noncentered processes that are difficult to control by a top-down approach.

Climate change is related not to one technology in need of replacement or adaptation but to a range of technologies that are interconnected with each other and the social system in which they are put to use. It is related to the full gamut of how energy services are provided (how energy is generated and consumed) as well as to what people eat and how and where that food is produced and how it is transported. To change the overall hydrocarbon-based energy regime, it is not possible simply to derive necessary steps from the goal to be achieved and execute them. Someone has to diagnose the dynamics and set out a transition path. Given the evolutionary character of sociotechnical change, the outcomes cannot be specified beforehand, and emerging irreversibilities must be traced and sometimes modified or counteracted.

Studies of attempts to orient technological change provide useful insights on the possibilities of redirecting technical change. Moreover, as the preceding sections show, analysts are able to introduce analytical reductions of complexity in various situations. This provides sufficient ground to develop ideas and suggestions.

In this section, we discuss ways to influence sociotechnical developments, with particular attention to the role of governments and to the possibilities for inducing a regime shift in energy technology away from fossil fuels.

*Attempts to orient technical change: from picking winners to modulating dynamics*

We start by considering the role of governments, for two reasons: they have de facto been involved in orienting technical change, and they have a responsibility for political processes of goal articulation and authoritative decisionmaking.

Government is but one of many actors and (as described in Vol. 1, Ch. 5) made up of different actors itself. Governments in all countries are in one way or another involved in technological development, through their science and education policy, industrial policy, health policy, environmental policy, and technology policy. Also, governments are often seen as having a special responsibility, in creating the right incentives, in priority setting and implementation (including funding), and in using their regulatory powers to exert force on technological development. Part of their job is to develop effective policy instruments to orient technical change in desirable directions. (For a general discussion of policy instruments, see Vol. 1, Ch. 5.)

In this section we discuss government experience with such policy instruments, and interpret and discuss them within the context of the insights from economics and sociology of technology. We start by briefly considering the traditional economist's argument for government intervention: the notion of market failure.

Markets, in principle and in themselves, are said to lead to efficient allocation of resources and a social optimum, but this does not happen in some situations because of the social inadequacy of private incentive mechanism, and because of indivisibilities, uncertainty, lack of appropriability, externalities and public good properties of knowledge (Metcalfe 1994). These situations are market failures, which provide a rationale for government interventions. Government support of basic research in universities, precompetitive R&D for industry, infrastructure, and military technology, all of which have public good characteristics and knowledge spillovers, has been justified this way.

In practice, governments do more. Technological missions such as space travel or the Oosterschelde flood barrier in the Netherlands are accepted as deriving their authority from a political decision to spend resources (in the same way as war efforts are not assessed against the market criteria of efficient allocation of resources). Equity considerations are another reason for government interventions in the economic process.

Market failures provide a general rationale for government intervention (and a specific rationale to intervene in climate change issues), but they do not prescribe in detail what governments should do (Edquist 1994), partly because externalities are ubiquitous and difficult to quantify. The market failure argument also puts policy into a static equilibrium framework which limits its usefulness in a world of cumulative and systemic change in technology. In the real world,

past technology decisions shape future possibilities, and myopic selection pressures operate against the development and uptake of new technologies, especially radical technologies with long development times that require complementary technologies and changes in social organization (Smith 1991).

The market failure argument provides an economic rationale for chosen policies. Most government policies with respect to technology are usually framed not as market failure but as desirable and undesirable technologies (and these policies have been criticized from the standpoint of market ideology). Alternative energy technologies such as photovoltaic cells, wind energy, and synfuels were stimulated in the 1970s, to become more independent from foreign energy suppliers and as a hedge against increasing oil prices. In the 1990s, solar energy is promoted for reasons not of diversification but of environmental considerations—which shows that the attributes that make a technology desirable may change over time. A certain measure of undesirability is visible in the way coal-fired power plants and gasoline-powered automobiles are now under increasing criticism (as other technologies and practices are), and this creates a diffuse pressure for change.

One very basic question is how governments can identify desirable technologies. This question is complicated by the relative distance of government from many technological developments. How to pick future winners? How to grow them into actual winners? Governments have developed policy instruments which combine the picking of winners (or avoiding of losers) with actual stimulation of their development.

One such instrument is the selection of appropriate areas of support for technology. Historically, military technology and health are selected as areas in which government support is considered to be warranted and needed. Nowadays, information and computer technology, telecommunications, biotechnology, and new materials are seen as strategic research areas as they offer a wide range of technological opportunities. Environmental technology is also supported through technology development programs. Technology foresight and appraisals are used to select technology areas and technologies that are appropriate for support. In other words, governments ask technology actors to help them in picking winners and growing them.

As in schemes of government subsidy in general, there is a danger that actors may submit risky or second-rate projects for subsidy. (Attractive projects will often be done anyhow.) In the value-for-money ideology, there will be no additional benefit and thus no good reason for a government to subsidize. However, there might be other reasons, such as increasing the stock of technological knowledge upon which government can draw in the future. What is second-rate now, might become first rate in different circumstances. So, governments are justified in subsidizing projects that are not immediately attractive to other



actors. But too much, and especially prolonged, protection will only create expensive failures. In some areas, governments often have no alternative but to support what appears to be desirable technology; an example would be the support of new worker-friendly technologies in the workplace. (A taxonomy and detailed discussion of the various support policies is given by Braun 1994).

Apart from technology development programs aimed at letting certain flowers bloom, governments also engage in weed pulling. They use regulation and taxation to cull undesirable technologies. Chemical pesticides that have a negative effect on health and environment are one example. Government standards act as a filter for subsequent technological developments. New chemicals and drugs, for example, are tested for efficacy as well as compliance with standards, and only those that survive testing (1 percent or less) are developed for production and market. The use of pollution taxes or taxes on products that give rise to adverse effects is another way of technology culling by providing a disincentive to the use of products and technologies judged to be adverse and changing the incentive structure in favor of more appropriate technologies.

Regulatory activities can be an indirect stimulus to the development of alternative technologies by stimulating the search for new solutions: "regulation is the mother of invention" (Ruttenberg, quoted in Ashford et al. 1985: 434). The question then becomes whether such a spinoff from regulation can be planned and secured. This question is the inverse of the traditional approach to technology assessment, where the technology is more or less known, and the impacts have to be anticipated. Here, the technology is unknown, or at least, has yet to be developed, although the required impacts are stipulated in the form of standards to be met by the technology.

Such a strategy of *technology forcing* sounds attractive: specify what you want, and the necessary technology will be developed. The possibility of technology forcing has been recognized and attempted, with limited success, in environmental legislation. The problem with technology forcing is that the government does not know what is technologically possible and economically feasible. Industry, with a better knowledge of technological possibilities, may use such information in a strategic way: it may promise to develop technological alternatives but keep such efforts at a low level in the expectation that the government will soften or postpone the standards when technological alternatives do not become available.

This happened in the case of automobile emissions standards in the US 1970 Clean Air Act. The 1970 Clean Air Act set out an ambitious scheme of strict emission standards (for carbon monoxide, oxides of nitrogen, and hydrocarbons) for new cars. It was inspired by a technology-forcing philosophy and criticized by industry as being overly restrictive. Although the car industry undertook research in low-emission vehicles, such attempts were perceived as

less than wholehearted (White 1982). The automobile manufacturers did not undertake a serious search for low-emission engines partly for strategic reasons. They expected that the laws would not be rigorously enforced upon them if they failed to develop compliance technology, and they were right: the standards were postponed by the US Environmental Protection Agency (EPA) in 1973 and 1975 and by Congress in 1974 and 1977.

In the end, the game shifted through third parties. Japanese motorcars started to compete in terms of lower emissions, demonstrating the potential for achieving emissions reductions. And *only* when the catalytic converter became available were the standards met.

This case shows some of the limitations of possibilities for government policies. Credibility is important: governments must be strict, and must be seen as strict to create some technology-forcing effect (Stewart 1981, Ashford et al. 1985). If they play the game well, governments can achieve some success.

One argument for the support of beneficial technologies is to increase the number of technological options, especially where new technologies are under-supplied by the market because the benefits are insufficiently valued (as in the case of environmental technologies), where new technologies have long development times (as in the case of energy supply technologies), or where the innovator has problems appropriating the benefits of innovation (e.g., when imitation is easy). Increasing the number of technological options may provide a hedge against shifts in the economic environment, against the revelation that a widely used technology poses a serious hazard, and against the danger that an inferior technology with an early start will come to dominate the market. The question is how much variety has to be created and maintained. Evolutionary modeling provides some answers, but only in the abstract. A practical approach derives from the branched, niche-based character of technological development, which is to create reservoirs or protected spaces for certain technologies, even when there is no immediate benefit.

With respect to weed pulling, the policy prescriptions are somewhat different. A command-and-control approach does not appear to be very effective, not only because a government agency does not have enough power, but also because it does not know enough about technological possibilities and future impacts (Stewart 1981). Economic incentives, such as pollution taxes, have the advantages that the government needs less information and that industry can choose the moment and method of compliance.

An evolutionary or technology dynamics approach differs from a traditional policy instruments approach. Whereas the policy instruments approach looks at how goals may be achieved through the use of policy instruments, the technology dynamics approach takes the goals not as given but as variable. It also takes issue with the idea of policy instruments as levers for achieving desired

technological outcomes: technological change is seen as a process involving many actors with different interests and capabilities, none of which is able to control the overall process. From this standpoint, government policies should be oriented toward the strategic interactions between the different actors, rather than laying down technological requirements. Regulation and the use of economic incentives now appear as one possible move in such strategic games.

In the strategic game approach, government can exercise its powers and influence by:

- changing the rules of the game by increasing the number of players (bringing in outsider firms with different interests and capabilities), prolonging the game when no satisfactory results are likely to emerge, empowering certain voices, promoting information exchange and learning, and stimulating cooperation between the actors
- acting as matchmaker by bringing together technology suppliers to work on a problem, providing financial assistance, manipulating technological and economic expectations – for example, by securing a (future) market for a new product
- organizing discussions between proponents and opponents, to generate improvements in understanding the issues and guide technology developers in their decisions.

The role of the government would then be that of an alignment actor and facilitator of change rather than that of a regulator. Such policies may be labeled as technological alignment policies.

Thus, government regulation is not always necessary. Voicing concern with respect to particular technologies may be enough to induce industry to look for alternatives. Of course, the threat of future regulation may be important. Given the information problem of the government, signalling by the threat of regulation may be a better means to stimulate technological innovation than actual regulations. The use of regulations may lead to lock-in adherence to technologies that are overly expensive or that have other serious liabilities. When there is uncertainty about what constitutes the best solution to a problem, experimentation is needed to learn more about technological possibilities and the desirability of the solutions. Thus, when regulations are used, it is usually preferable that they be flexible with respect to technical choices and responsive to new scientific evidence about the seriousness of the problem at hand.

Technology-forcing regulation appears as one possibility. In addition, even without explicit regulation, governmental and other forces will act on technological development. If a technology and type of behavior by industry is seen as unacceptable, firms will always experience pressures (from customers, employees, environmentalists) to change their behavior. These pressures act as stimuli for technology development and can be seen as diffuse technology

forcing. People want firms not only to deliver goods and services but also to behave in a socially responsible way. The public climate generates a credibility pressure on firms: they lose goodwill if they neglect environmental issues too openly. When the early synthetic detergents of the 1960s created very visible environmental problems (foam in surface water), the detergent companies and especially their suppliers developed new processes leading to biodegradable synthetic detergents, without government regulation (although with the expectation that there might be regulation in the future).

As another example, the UK Chemical Industries Association instituted a Responsible Care program to restore public trust. The program includes promoting environmental management standards and improved public communication (Simmons & Wynne 1993). These credibility pressures are most strongly felt and taken up by top management, not by the middle management (Steger 1993).

When impacts are more diffuse (safety, user friendliness, employment, other social impacts) and their desirability is controversial, governments are less able to force technology. In such cases, governments have much less immediate leverage than in the case of visible environmental impacts. But credibility pressures may still help, and effects may occur even without government action.

The point is that technology transformation can be facilitated by external influences; strategic interaction and the role of third parties (such as public opinion) must be taken into account. The question of people's wants can then become part of modulating continuing transformations. Instead of governments specifying what is desirable and which are preferred directions, these can emerge from the process itself. Goals or criteria of desirability are introduced interactively, in a societal learning process.

This position contrasts with the widely cited *control dilemma* identified by Collingridge (1980). He argued that technology control faces an information problem (impacts cannot easily be predicted until the technology is extensively developed and widely used) and a power problem (control or change is difficult when the technology has become entrenched). Together, the two problems create a dilemma: influence appears to be possible only at the stage where impacts cannot be well enough foreseen to orient the development in particular directions. Collingridge therefore advocates flexibility of technology. Although this is a good thing in principle (in line with the proposal to create technology reservoirs), it neglects the necessity of physical and institutional entrenchment of a technology: without adaptation of infrastructure (including other technologies) and without (vested) interests, there will be no technology at all. Realization of a technology implies a measure of inflexibility.

In phrasing his control dilemma, Collingridge (consistent with other critical analysts) assumes a non-evolutionary, noninteractive development of technology. After an initial decision to develop a technology, development and impacts

are necessary, even if unforeseeable, consequences of this initial decision. The many choices and decisions that lead to the development and realization of a technology are neglected. Actors, in fact, exert themselves to domesticate and control the technology, with some success. The problem thus becomes one of changing the dynamics of control, instead of controlling what was not controlled before. The role for government is to act as a creative game regulator and an alignment actor rather than a regulator.

*An exemplary analysis of inducing sociotechnical change*

This section analyzes the possibilities for inducing large-scale technical and corresponding sociostructural change in energy-supply and -using technologies, on the basis of the evolutionary theory of sociotechnical change. This analysis complements and sometimes replaces the approach of economists and engineers who have an important input in greenhouse gas abatement policies (see Ch. 4, and Vol. 3, Ch. 1).

In the global climate change debate, the primary role of economists has been to assess and compare the costs and economic benefits of possible measures for reducing greenhouse gas emissions. For this purpose, economists have typically adopted a top-down approach: aggregated econometric models are used to generate predictions about changes in the energy mix and energy efficiency. Underlying the models' results are assumptions about growth in gross national product, population growth, behavior, resource reserves, and costs of primary energy inputs. The effects of economic instruments such as carbon taxes and tradeable emission rights are analyzed. That is, in the models, price changes govern the process of energy savings and shifts in energy mix. Some engineering studies also predict market penetration levels of emerging energy technologies. These are bottom-up studies based on detailed knowledge of energy technologies and of the markets in which they may be used.

These two kinds of models are now the main tools to assist policymakers in designing policy measures for dealing with greenhouse warming and climate change. Unfortunately, both types of approaches suffer from rather simplistic assumptions about the dynamics of energy substitution and technological change. As Kirsch (1992) writes, the top-down studies either assume autonomous improvements in energy efficiency or posit the existence of backstop technologies that become economical at an externally specified threshold price. Furthermore, the social context remains essentially unchanged, whereas in reality important new technologies transform the system from which they emerge. The bottom-up studies, by contrast, draw from a predetermined set of technological options. That is, technological heterogeneity is specified beforehand, rather than being the outcome of coevolutionary processes. The possi-

bilities of radical innovation on the one hand and the impact of various learning effects on the other are neglected in favor of fixed coefficients for known technologies. Moreover, even after the set of available energy technologies has been specified, the predictions depend upon assumptions about whether or not economic agents (public and private) will choose these options (Kirsch 1992).

These analyses neglect the effects of technological regimes and sociotechnical landscapes. For example, *Renewable energy* (Johansson et al. 1992) was commissioned by the United Nations Solar Energy Group on Environment and Development as input to the 1992 UN Conference on Environment and Development in Rio de Janeiro. The book contains a figure showing the lifecycle costs for motorcars powered by alternative energy systems: batteries, fuel cells (fueled by hydrogen, ethanol, or methanol), and internal combustion engines. According to this figure, the costs of owning and operating an automobile powered by alternative renewable fuels are almost the same as—and in some cases even slightly below—the lifecycle costs per kilometer of an internal combustion engine fired with gasoline (at the price projected for the United States in the year 2000). This raises the question why alternative fuel vehicles have not made an impact so far, and why they are not likely to do so in the near future.

To answer this question we must step outside the concentric view of technology as artifacts characterized by functional parameters. Motor vehicle engines are an essential part of a highly complex technology, which has benefited over the past century from a wide array of product improvements in terms of reliability, durability, speed, range, fuel efficiency, and is embedded in production systems and lifestyles. The automobile depends for its manufacturing on a production system and organizational structure that is complex and capital intensive. This makes it extremely difficult for new firms to successfully enter the business. The automobile is also part of a larger technological system involving a road infrastructure, gas stations, repair shops, and training, and it extends into the social and cultural realm as a symbol of freedom and a signal of status (Sørensen 1991).

Thus, despite considerable detail, engineering studies of alternative energy technologies fail to provide a realistic description of how the technology development and selection process interacts with the socioeconomic system in which it emerges. The concepts of sociotechnical landscape and of technological regime provide leverage on these complex questions. For the issue of inducing and orienting change, understanding the concept of technological regimes is the necessary entrance point.

For its operation, the present economic system depends on energy carriers almost totally based on fossil fuels—coal, oil, and natural gas. Worldwide, these three energy sources supply about 90 percent of the energy that is being purchased and put into use in the economic system (Gray et al. 1991). Coupled to

these energy sources are conversion and end-use technologies in which energy is converted into useful energy forms and energy services. We can speak of a *hydrocarbon regime*, with coal as the main source to generate electricity, with gasoline produced from oil as the main transport fuel, and with natural gas as the primary source for space heating. How can the present regime be reoriented toward sustainability? Basically two routes exist: the first is to adapt the existing system to environmental pressures (such as advanced fossil-fuel energy-conversion technologies and oxides of nitrogen emission control systems); the second is to make a shift to a different technological regime based on different energy sources and technologies and engineering knowledge. Both routes require sociotechnical change; the second raises the additional challenge of a transition path from the present regime to a different one.

The basic question is how new possibilities, which in time can grow into radical innovations, can survive and grow, and in the end successfully compete with well-developed technologies in an entrenched regime. To identify general transition paths, we briefly turn to historical changes of regimes.

Earlier we noted that powerful mechanisms reinforce the entrenchment of a technology in the socioeconomic system. Radical innovations must compete with well-developed technologies that have gone through a series of incremental improvements, have gained precise user understanding, and are integrated in the economic system and social life. One transition path is a specialized market in which the new technology could be used. In the case of steam engines, deep-drainage mining provided a niche. Automobiles claimed several niches. Automobiles were first used by the aristocracy (in Germany and France), who were eager to develop an alternative for the mass transport based on horse carriages. The ability of automobiles to climb all hills and drive long distances made them attractive for physicians who had to visit patients living in remote places. Adoption of automobiles by US farmers, who were seeking ways to overcome their relative isolation, turned them into a product with a mass market. Niches, this example demonstrates, are important for the further development of a new technology: demonstrating the viability of the technology makes it possible to attract investment, and gain support from other firms and public policymakers.

Another version of protection against harsh selection is the benefit from accumulated experience in other sectors, and from the presence of a network in which it can be easily introduced. The automobile owed part of its success to the bicycle. Experience accumulated in bicycle production was put into good use in the automobile industry, and a road infrastructure was already present. Existing components and products could often be incorporated in, or combined with, new technologies. Only gradually can the new technology draw out its own allies and become the heart of a new regime.

Given the importance of niches and their branching out into what may become a new regime, the next important issue is to create niches to be productive for further development. The quasi-evolutionary model of technological development offers a good starting point to analyze actors' strategies and interactions. Actors appear to have three strategies to anticipate and influence the selection environment: voicing and articulating expectations; shaping of technological nexuses, institutionalized carriers that link the variation and selection process and thus allow mutual, simultaneous action; and creating niches or protected spaces in which new variations are exposed to selection pressure in a controlled way and thus protected against excessively harsh selection.

Voicing expectations and selling promises are especially recognizable in new technological missions, but they play a constitutive role also in mobilizing resources for a protected space to nurse a promising lead (Van Lente 1993). Nexuses provide institutional infrastructure for linkages between variation and selection (or just supply and demand). Niches could protect a new technology forever, but the gradual reduction of protection is important to induce a viable transition path. Thus, the niche idea is linked with the general recognition that successful innovations must couple user requirements and demand. Examples of such niches and a new technological nexus can be seen in special teams within a firm combining people from R&D, production, and marketing, protected so as to enable dedicated work on a novel product. In mixed private and public developments, government agencies can play a role in setting up niches and helping them evolve.

The creation of niches for alternative energy technologies is an interesting option from a climate change mitigation perspective. It is one possible way to construct a transition path to an alternative energy system, perhaps the only possible way, given the disruptive effects of traditional standards and tax policies that limit their feasibility and potency (Kemp et al. 1997). Such a policy must contain a developmental component, and can therefore be called strategic niche management. Strategic niche management is the planned sequential development of protected spaces for development and application of a new technology. Strategic niche management has four aspects (Kemp et al. 1998):

- to articulate the necessary changes in technology and in the institutional framework for the economic success of the new technology
- to learn more about the technical and economic feasibility and about the social benefits and disadvantages of different technology options—that is, to learn more about the desirability of the options
- to stimulate the further development of these technologies, achieve cost efficiencies in mass production, promote the development of complementary technologies and skills, and stimulate changes in social organization that are important to the wider diffusion of the new technology



- to build a constituency behind the new product—of firms, research institutes, public agencies, and users—whose semicoordinated actions are necessary to bring about substantial shift in interconnected technologies and practices (Miles 1993; see also Molina 1993).

Strategic niche management is multiactor oriented and aimed at generating positive feedback through interactive learning and adaptation. It differs from traditional demand policies aimed at the wider diffusion of well-developed technologies, and from the supply (or technology-push) approach, which does not integrate knowledge and expertise of users and other actors into the technology development process. Institutional adaptation is part of its remit, so it links up with the level of evolving regimes.

What are the elements of an effective public policy for the productive creation of a niche? Possible elements are the formulation of long-term goals, the creation of an actor network, the use of standards, supplemented by tax and subsidies policies. Any such policy must exhibit a good understanding of the barriers to introducing the environmentally benign technology into the relevant sectors. Barriers may be economic, that is, the new technology is unable to compete with conventional technologies, given the prevailing cost structure. They may be technical, in the form of a lack of complementary technologies and lack of appropriate skills. They may be social and institutional, having to do with existing laws, practices, perceptions, and habits. To deal successfully with these barriers, an integrated and coordinated policy is called for.

The Los Angeles initiative to promote electric vehicles is a good example of an integrated policy. Although the policy is primarily aimed at reducing photochemical smog (a notorious problem in the Los Angeles area), it illustrates how strategic niche management may be used to induce radical changes in the hydrocarbon-based energy system. By requiring car manufacturers to mass-produce zero-emission vehicles, the policy overcomes the technological stalemate in which car manufacturers are reluctant to introduce electric vehicles for fear that consumers will not want to purchase alternative-fuel cars, whereas demand for electrically powered vehicles cannot develop if electric vehicles are not for sale. According to California rules, zero-emissions cars must account for 10 percent of new car production in 2003, and strict standards for hydrocarbon and nitrogen oxide emissions are being set for all new motorcars to be sold in the 1994–2003 period (Templin 1991).

Part of the program is a competition, under which the three winning manufacturers are to build a variety of small cars, passenger vans, and light commercial trucks to create a 10000 vehicle zero-emission fleet by the year 1995 (*Financial Times* Survey 1990). The whole initiative is jointly sponsored and is being overseen by the city council, its Department of Water and Power, and the private sector utility, Southern California Edison. The department and

Southern California Edison are providing development funds to the chosen companies. In addition, they are devising, with both state and federal authorities, fiscal incentives to make usage of such cars attractive.

In another initiative, the City Council of Los Angeles has formed a task force on electric vehicle (EV) infrastructure. This has resulted in several actions to stimulate the use of EVs, such as building-code requirements for new construction to ensure that houses have adequate EV charging facilities, a requirement that the city provide EV charging facilities, preferential parking or charging facilities for EVs, incentives for airport-area hotels and car rental companies to use EVs as shuttle vans, and a requirement that the Los Angeles airport uses a certain number of EVs.

The California approach to introducing electric vehicles is a combination of technology-forcing standards and wide range of facilitating initiatives. The initiatives have defined a future space and market for a new technical artifact: the electric car as a zero-emission vehicle. The promise of a future market for electric vehicles not only caused automobiles manufacturers to invest in electric vehicles, it also attracted outsider firms. Many small and new firms started to trade in the market of promises. They did so by developing new options and concepts. They expect to be able to produce for the niche markets that will evolve, but not for mass markets, as they lack financial strength and distribution facilities. Importantly, their role is not limited to that of market actor in the traditional sense. Some of these new firms act as central nodes in the new market. They perceive their own role as platforms. They act as a meeting ground for a large variety of organizations, including industry, utilities, government agencies, and educational and research institutions (Schot et al. 1994).

The California approach is quite different from that taken by the Netherlands. In the Netherlands, the approach is to seek and develop specific niches for EVs through a coordinated effort of all important actors. This is done within a multiyear program coordinated by an organization called NOVEM which implements and develops R&D programs for the Dutch Ministry of Economic Affairs. In contrast to California, where the many cars (and thus mobility) is taken for granted, in the Netherlands mobility itself became an issue. A broader range of pollution reduction options is on the agenda, including increasing gasoline and other taxes. Some critics defined EVs as a nonsolution from the perspective of reducing mobility. The problem of open goals and means was partially addressed when government ministries (and other actors) defined EVs as an attractive transport option for a specific market or usage niche: that of cities. Especially in cities, internal combustion vehicles contribute to pollution by cold-engine inefficiencies, frequent acceleration and deceleration, inefficiency at low speeds, inefficiencies of the catalytic converter, and so on. The limited performance and geographical range of EVs between chargings is also

less of a problem in cities. In such an environment, EVs are seen as an attractive alternative to internal combustion vehicles.

The Dutch experiment with EVs was designed in such a way that a broad learning process was enacted involving many parties. The results of the experiment can be characterized as a series of articulation processes: the articulation of technical problems (in particular, the malfunctioning of batteries), the articulation of user requirements and experiences, a clearer picture of who would be attracted to the technology (fleet owners such as taxi companies, delivery firms), how limitations of the technology could be overcome through driving behavior and planning of trips, the identification of regulatory constraints, and, finally, how Dutch industry could benefit from the EV market (Schot et al. 1994).

An example further from market readiness is hydrogen, considered an ideal transportation fuel from an environmental point of view. Hydrogen has a high energy efficiency and does not emit carbon dioxide as a product of combustion. If noncarbon energy technologies such as renewables or nuclear power are used in the production of hydrogen, it becomes even more attractive from a climate change mitigation standpoint. Hydrogen may be used in internal combustion engines or in fuel cells to supply power. Again, although technically feasible, the high costs of using hydrogen presently pose an enormous barrier. According to Jackson (1992), using estimates from various authors, the economic costs of a hydrogen-fueled car using electrolysis and photovoltaics to produce hydrogen are estimated in the range of \$1 and \$5 per kilometer, whereas the economic costs of a conventional car are between \$0.05 and \$0.10 per kilometer. These figures are for 1990, and further cost reductions and efficiency improvements are to be expected from future advances in fuel cells and photovoltaics. However, to achieve or accelerate the transition to an integrated hydrogen economy, the creation of a niche could make an important contribution.

Airplanes constitute a good candidate for a hydrogen niche in the transport sector. Within the aircraft industry, hydrogen is already considered a potential commercial aviation fuel. In the early 1990s, 15 German and Russian firms, under the leadership of Deutsche Aerospace Airbus GmbH (DASA), have investigated the possibility of using hydrogen. They were involved in the design of a large passenger airplane fueled by liquid hydrogen, the cryoplane; they hope a prototype will be ready by the year 2005 (Raaymakers 1992).

Whether a hydrogen-fueled airplane will be mass produced and will find its way into the market within the next 15 or 25 years is unclear. Several barriers hinder the introduction of the cryoplane in the commercial market: the high costs of hydrogen compared to kerosene (so far the only fossil fuel that is not taxed), the buildup of an infrastructure to mass produce hydrogen, the distribution of hydrogen in various parts of the world, and safety and environmental problems (for example, although it does not emit carbon dioxide, it emits water

vapor, which at high altitudes contributes to the greenhouse effect). In this case, expectations and alignment of resources are crucial to start up the niches necessary to explore what could become a transition path.

Strategic niche management is not just a useful addition to a spectrum of policy instruments. It is fruitful, and perhaps even necessary approach to transform unsustainable regimes. But there are also problems with the creation of protected spaces for promising technologies.

- Policymakers must find a balance between protection and selection pressure. Too much protection may lead to expensive failures, and too little protection may disclose different paths of development. This calls for continuing monitoring and evaluation of coevolution processes and of the support policies themselves.
- Success is not guaranteed; changing circumstances may make the technology less attractive and technological promises may not materialize. Hence, it is important to promote technologies with ample opportunities for improvement, with a large cost-reduction potential that can be applied in a wide range of applications. Then, even if the technology does not yield short-term benefits, it may well be a useful technology in the longer term. For example, government support of electric vehicles has been criticized (e.g., Wallace 1995) on the grounds that the environmental gains are limited and that their performance is poor compared to internal combustion engine vehicles. But this need not be true in a long-term vision where electricity is generated by solar energy and advanced batteries become available. Improved batteries may also pave the way for hydrogen-powered automobiles and the wider use of solar energy.
- Governments will encounter resistance to ending support for a technology because of the investments that have been made and resistance from those who benefit from such programs and whose expectations may have been falsely nourished.

This analysis of strategic niche management in energy technologies argues for a particular approach and also exemplifies the importance of attempting to modulate continuing dynamics, to align technological supply and demand, rather than just pick the winners. The potential of combining short-term and long-term benefits, as well the challenges in doing this well, are illustrated by our discussion of strategic niche management.

*Conclusion*

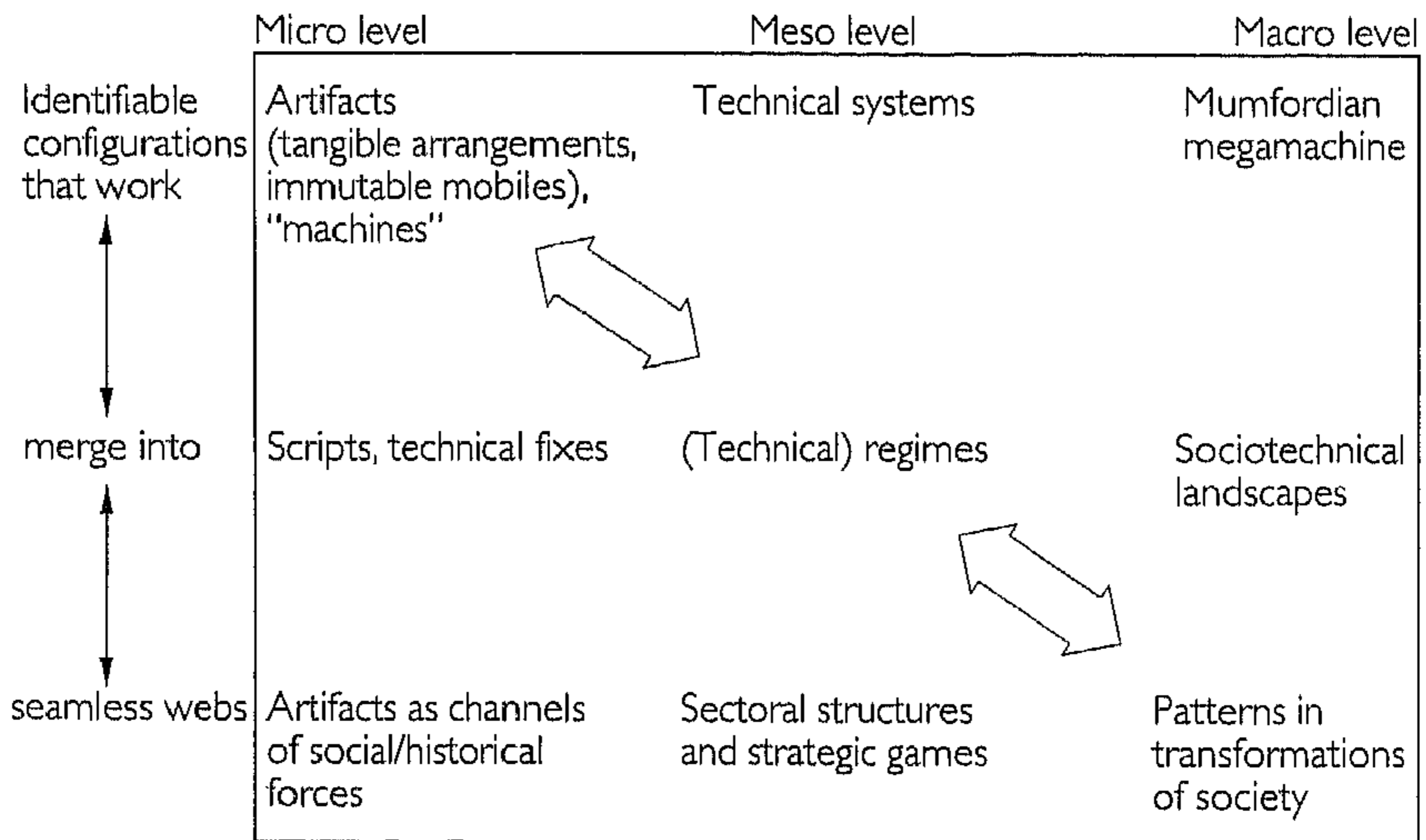
This chapter began with a fundamental question: what is technology? The social sciences (and humanities) conceptualize technology in different ways, from things and skills to a more abstract, less nuts-and-bolts notion of technology as a transformer of input into output to material culture or sociotechnical landscape. The chapter focused on the important issues surrounding the dynamics of technical change and their outcomes, particularly in relation to attempts to orient technological developments. We have presented findings from recent economics, sociology, and history of technology, especially as they emerge from interdisciplinary technology studies. We then added policy analysis to address the question of productively guiding technological development in desirable directions. The focus on dynamics of technical change and how to manage it has important implications about the role of technology in climate change and the expectation of many researchers and policymakers that sociotechnical change will be important to resolving the issues of climate change.

Instead of a traditional view of technology as tools, and the skills to build and handle them, we characterize technology as configurations that work. The importance of this characterization is that it avoids the individualistic bias of a tools concept, and so can include large technical systems. Artifacts, procedures, and humans can be part of a configuration; Mumford's concept of a megamachine (e.g., a city) emphasizes this view.

A comparable view centers on the hardware and through concentric structuring implies a one-way causality, from new technology to society. The very real risk is that technology as artifacts is seen to be located outside society and treated as an exogenous factor affecting society—the cannonball view of the impact of technology. Such exogenous views of technology used to be current in sociology and especially economics, but major progress has been made in endogenizing technology.

The portrayal of technology as developed in R&D establishments and industrial firms, and then transferred to the marketplace, is only part of the story of technology in society. Other aspects include the heroism of novelty creation, the messiness of implementation and introduction, and the aggregate of myriads of little decisions that underlie the development and embedding of technology in society. All these elements comprise continuing sociotechnical transformations.

The evolution of technology can be conceptualized as novelty and growing irreversibility. This basic dynamic is played out at several levels. At the level of artifacts and systems, more or less immutable, are mobile configurations that work. At the level of technological regimes, such as computer regimes or the hydrocarbon-based energy regime, are many commitments, sunk investments,



**Figure 6.3** The multilayered backdrop of novelty and irreversibility.

and institutionalized practices that evolve in their own terms and are hard to change. And at the level of sociotechnical landscapes are the physical infrastructures, artifacts, institutions, values, and consumption patterns—the material culture of our societies—which are the backdrop against which specific technological changes are played out. It is important to include all three levels, because technology’s implication in climate change is as much through socio-technical landscapes and technological regimes as through particular artifacts.

To visualize the different levels and linkages in the technology–society complex, we reproduce Figure 6.1, but with the important addition of two arrows (Fig. 6.3).

Along the horizontal axis, the scope of the configurations that work and of the technology–society complex increases. This includes the concentric view but is not limited to it. The vertical axis indicates the inclusion of technology into ever broader seamless webs in social and economic life, sectoral structures, strategic games, consumption patterns, and lifestyles. Central to Figure 6.3 are technological regimes, the coherent complex of scientific knowledges, engineering practices, production process technologies, product characteristics, skills and procedures, and institutions and infrastructure that are labeled in terms of a certain technology (e.g., a computer) or mode of work organization (for example, the factory-based system of mass production). Technological regimes are a broader, socially embedded version of technological paradigms.

Technological regimes are the intermediary between specific innovations as they are conceived, developed, and introduced, and the overall sociotechnical

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landscape. Novelty originates within existing regimes, starting at the micro-level of local practices. New technologies are always introduced against the backdrop of existing regimes and sociotechnical landscapes. They do not come into the world with their possibilities well defined, and their success is linked in some way to structural problems or even crises of existing systems. New technologies become more robust as they benefit from dynamic scale and learning economies and institutional adaptations, and find new applications. In this process, irreversibilities increase, and a reversal occurs. The technology becomes a force of its own, the new configurations become part of the sociotechnical landscape and thus the context for newly emerging technologies, setting the terms of competition for other technologies. Having broken one set of sociotechnical relationships, it now fixes others.

What is usually called technology diffusion is really a transformation process by which a new technological regime grows out of the old regime. Technology adoption is an active process, with elements of innovation in itself. It is connected with the availability of new technologies, with expectations, new skills, management systems, new supplier–user relationships, changes in the regulatory framework, and new ideas. Behaviors, organization, and society have to rearrange themselves to adopt and adapt to the novelty. Both the technology and social context change in a process that can be seen as coevolution.

The evolution of the multilayered technology–society complex implies that technology is not an endless reservoir into which firms or powerful actors can dip and which responds to their interests. In contrast, recent technology studies emphasize the nonmalleability of technology and explain it not in terms of some inherent characteristic of technology but as the outcome of processes of cumulation and learning that cannot then be reversed. Evolutionary, quasi-evolutionary, and sociotechnical theories have addressed this question, and their insights can be used to derive guidelines for attempting to orient technological change.

An important insight is that the eventual shape of a technology, the purposes for which it is used, and the way in which it is embedded in society, may be different in five or ten years' time. How it will look is difficult to predict. Technological development is not a continuous process along dimensions of increasing performance and functionality. It is more like the way that yeast cells grow; developments branch off in different directions, cross-connections and interactions occur (among technological regimes, firms, and other actors). Secular changes also occur—of mechanization, automation, and control—that affect the development of technological regimes.

A second insight is that many new technologies can survive because of niches, that is, relatively protected spaces in which a new technology can be developed and applied. Fledgling technologies are, almost by definition, weak

compared with the dominant regime; they can survive only through protection or finding specialized markets.

A third finding is that the multiactor processes of technical and social adaptation in which problems and conflicts are gradually overcome can be understood as a process of coevolution of technology and society, or, when focusing on markets, as the coevolution of technological supply and demand, which interact with each other. Suppliers learn from user experiences and benefit from economies of scale, and users develop a better understanding of the technology, how they may use it for their own benefit, and what they want from it. In the interaction process, misfits between the technology and the social environment are accommodated through processes of learning, coercion, and negotiation. Because demand is articulated in interactions with supply, policymakers should avoid too-easy recourse to demand simulation policies. Rather, they should stimulate learning and articulation of demand, especially when users do not have precise requirements for novel technologies.

The coevolution process can lead to a relatively stable situation, in which further technological developments are patterned and can be mapped. When the design hierarchy has not stabilized, but is in flux, decisionmakers cannot map along clear dimensions and they have to fall back on tracing niche-building and niche-branching processes. As economists have shown, such processes are strongly path dependent, and lock-ins (and lock-outs) can easily occur.

Can processes of sociotechnical change be guided in desirable directions? In the usual policy instrument approach, policymakers look for drivers and levers to exert force in a known direction. Although such an approach may be possible where patterns and responses are predictable, it is not adequate for situations in flux, nor can it address the complexity of the multilayered complex of sociotechnical change. A more heuristic approach is necessary, where policymakers look for points of attachment to the evolving sociotechnical landscapes.

Guiding technological developments appears to be more manageable than guiding or shifting technological regimes (also in relation to sociotechnical landscapes). But even guiding technological developments is a significant challenge. The goals are rarely clear, or clear enough to specify requirements. Desirable directions cannot just be stipulated. Finally, the nonlinearity and branching nature of technological development and diffusion, together with the processes of co-production of societal impacts, make extremely problematic the connection between a goal (a desired situation in the future) and specific action with regard to technological development.

For governments, a command-and-control approach is not feasible; with the nonmalleability of technology, governments cannot call up desirable technologies by legislation. Incentives and constraints (including regulation) do have effects, but governments cannot gauge their content and timing. In addition,



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governments have little knowledge of technological possibilities; they act on the basis of technological promises. According to analysts such as Collingridge, this leads to a control problem: in principle, governments have the greatest influence over technological choices when they know the least about the impacts and desirability of the technology; when the technology is fully developed and widely used, it is extremely difficult to control it (because of vested interests and high adjustment costs).

This dilemma of knowledge and control applies to all actors involved in technological development. Indeed, technology is continually shaped by actors who exert themselves to domesticate and control the technology, with varying degrees of success. Technology is not out of control, but the dynamics of control do not always lead to acceptable outcomes.

As we draw on fundamental understanding of processes of technological development, we can identify and define opportunities for productive intervention in the process. Intervention should be seen as modulation of continuing transformations.

Government modulation of the dynamics of control should be oriented toward the strategic interactions among the different actors rather than just laying down functional requirements. Government might intervene to change the processes involved in technology development: facilitating communication, broadening the scope of inquiry, supporting participants that might not otherwise be heard, providing resources for research unlikely to yield short-term results, and stimulating cooperative activities in a novelty-seeking business environment. For example, government can secure a future market for a new product. Or, in the case of technological controversies, government can facilitate discussions among interested parties, to generate better understanding of the issues, and guide technology developers in their decisions. Thus, the role of the government is that of an alignment actor and facilitator of change rather than that of a regulator.

For climate change, it is as important to shift the hydrocarbon-based energy regime as it is to develop particular new technologies and systems. Just as technological trajectories branch and shift, so can policymakers think of a transition path toward a new regime and apply themselves to bring this about. Since technologies initially grow best in niches, protected spaces for further evolution without the full force of selection being felt, policymakers can actively create such niches. As the technology becomes established, steps can be taken to reduce the protection afforded by the niche. Positive feedback through interactive learning and institutional adaptation occurs and, by creating a little bit of irreversibility in the right direction, the transition process is pushed forward. Transition paths are created in the attempt to traverse them.

As a policy instrument, strategic niche management promotes technical

change in directions that offer both short-term and long-term benefits. This is not to say that success is guaranteed; it is an example of a heuristic approach, exploiting points of attachment in an evolving sociotechnical landscape. On the other hand, by drawing on our understanding of the nature and dynamics of technological development, it definitely is a realistic approach.

Having made some progress in understanding the dynamics of technological development, we can and should return to the normative questions of goals, desired directions, and power gradients and asymmetries. Goal setting for technological development depends on broader agenda-building processes in which goals are weighted against each other, a process in which promises about new technology play an important role. A challenge in defining desired directions for technology would be to think about what is progressive and what is conservative about technologies, and thus set in motion a technologically informed public and political debate.

To understand the role that power asymmetries play within technological development, we can look at strategic interactions among industry, government, and other actors in the context of (technological) uncertainty, asymmetry of information, and multiple goals, and from there look at technological developments.

Another fertile field of inquiry would be into long-term sociotechnical transformations, including cultural aspects such as the aspiration to modernity. Climate change could then be located in a more general diagnosis of what industrial societies are doing and what this implies—also for possibilities to address global climate change.

Using waves or clusters to capture something of long-term transformations can be a first step. Looking at the keywords used for the present fifth Kondratiev wave and comparing them with earlier development modes, differences appear. In the late eighteenth century, individual agency is highlighted. In the late twentieth century, regimes, clusters, and policy seem to be keywords.

Clearly, technology is explicitly taken up in strategies and policies of governments and firms, and new actors—in the international arena represented as nongovernmental organizations—become involved (see Vol. 1, Ch. 5). And this creates a demand for understanding the nature and dynamics of technology.

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