# Path Dependence, Network Form, and Technological Change

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A process of economic allocation is called *path dependent* when the sequence of allocations depends not only on fundamental, *a priori* determinants—typically listed as technology, factor endowments, preferences, and institutions—but also on particular contingent events. Instead of converging to a determinate, predictable, unique equilibrium, such processes have multiple potential equilibria, and which one is selected depends on the specific history of the process. Positive feedbacks among agents' choices lend persistence and, indeed, increasing impact to particular early choices and other events.

Under what conditions is an allocation process path dependent? I address this question, first, by synthesizing elements of previous answers, focussing on the conditions under which allocation is determined over time rather than at a single moment. Second, I extend my answer by focusing on two issues: first, the form or graphical structure of the explicit or often "virtual" networks that characterize the interdependency of agents' choices and thus the structure of positive feedbacks and, second, the specific characteristics of technology and technological change, which in various ways affect the relative attractiveness of different potential equilibria and the permanence of "lock-in" to a specific path of allocation. My emphasis here, like that of most of the literature, is on path dependence in technology—specifically, in the selection of specific techniques. After developing this theme, I also briefly apply the ideas here to what David (1993) has called the homomorphism of path dependence in technology, institutions, organizations, and other matters.

Paul David (1985, 1987) specified three conditions which may work together to make processes of technological change path dependent: the technical interrelatedness of system components, quasi-irreversibility of investment (or, more generally, switching costs), and positive externalities or increasing returns to scale. These conditions lead agents to coordinate their choices and also lend persistence to the resulting allocation.

W. Brian Arthur (1989, 1994) focused attention on a single condition: increasing returns to adoption that are realized not at a single point of time but rather dynamically. These increasing returns may arise either on the supply side of a market as a result of learning effects (learning by doing or by using) or on the demand side as a result of positive network (or agglomeration) externalities that raise the benefits of a technique, product, or location for each user as the total number of users increases. Either case results in a positive feedback from the macro state of the system to the choices of individual agents, possibly resulting in de facto standardization on a single technique.

By contrast, the most prominent critics of the concept of path dependence, S.J. Liebowitz and Stephen E. Margolis (1994, 1995), called attention to two conditions under which allocation processes are *not* path dependent: first, foresight into the effects of choices and, second, opportunities to coordinate agents' choices through communication, market interactions, and the appropriation and promotion of alternative techniques—in short, actions that internalize the mutual externalities of agents' choices. They argue that purposeful behavior overrides the purposeless mechanisms that they understand to be the basis of path dependence, and that path dependence can therefore affect only aspects of the economy that no agent has an incentive to change—and that neither economic agents nor economists have a reason to care about.

As we will consider, economic agents often act under conditions of limited foresight and limited internalizability, and their purposeful actions show that they both care about and take account of that fact. Because these conditions are both prevalent and interesting, economists should examine explicitly how they affect the nature and outcomes of an economic allocation process.

These considerations of the conditions for path dependence are complementary in ways that I examine in the following section. Even together, however, these considerations do not explain differences in the outcomes of empirical cases that fulfill the conditions. For example, some cases result in a single, "global" de facto standard, others in multiple local or subnetwork standards. Some cases of standardization or "lock-in" appear permanent, but some have given way to new standards, sometimes showing a tendency to converge to an optimal technique. Externality-internalizing behavior proves fully compatible with path dependence in some cases but not in others. The latter part of this article offers a partial accounting for these differences.

## Toward a Systematization of the Conditions for Path Dependence

Our path toward a fuller characterization of the necessary and sufficient *concrete* conditions for path dependence begins with Paul David's (1999) reflections on the ultimate *abstract* conditions: First, there must exist multiple, *diverging* feasible paths of allocation, each one locally *stable* so that agents are not "led back to a single, globally stable attractor of the kind that characterizes an ergodic dynamical system."[1] Second, the factors or criteria that select among these branching paths must be to some extent "orthogonal" to any system-level economic issues at stake—for example, efficiency. This means, in part, that "the actual path of development must ... be an emergent system property whose 'selection' was an unintended consequence of the interactions among agents that were not engaged in any conscious collective choice." A process for which the path to be taken is itself an object of choice is not path dependent.

The divergence of paths noted under the first condition is, straightforwardly, the result of positive feedbacks, the increasing returns to adoption identified by Arthur. In David's terms, this may be the result of technical interrelatedness combined with increasing returns or positive externalities. As both Arthur (1989) and David (1985) note, positive feedbacks may end if increasing returns are bounded or exhausted at a sufficiently low level.

The local stability of paths is largely the result of quasi-irreversibility of investment—high switching costs. If the decisions that put an allocation process on one path are costlessly reversible (including in terms of information and transactions costs), then the process can always move to the path that is revealed as optimal. Less strictly, if switching costs are positive but still sufficiently low relative to the gains from switching, then a path revealed as suboptimal loses its local stability. As we shall see, both the costs and benefits of switching may vary with the state of technology, and new technology may bring an end to the local stability of a particular path.[2] Furthermore, the private and social costs and benefits of switching depend on transactions costs in internalizing the externalities prevalent in path-dependent processes. These transactions costs may be quite high under conditions of strong

[1]An ergodic system is one in which the distribution of states that the system can assume becomes independent of particular past states.
[2]From another perspective, this is not the end of local stability but rather the reconvergence of different paths.

technical interrelatedness and institutions that set the interests of different agents against one another, as Scott (2001) showed in a study of Britain's "coal wagon problem." However, the innovation of new internalization mechanisms (generally organizations or institutions) may lower transactions costs and so bring an end to the local stability of a particular path.

The second of David's conditions, the lack of a close link between factors that select among alternative paths and the system-level economic issues at stake, is what gives room for the impact of particular contingent events, that is, events not necessitated by systematic, *a priori* factors. These contingent events may be either purposeful choices by economic agents—for example, variations in strategy motivated by idiosyncratic beliefs about unproven technologies and unexplored markets—or else "historical accidents" that are exogenous from the point of view of these agents. In either case, such events are the sorts of things that management scholars and the business press cite as reasons for the relative success of different firms, but which are not yet sufficiently incorporated into economic theory.

What can cause this divergence between the factors that select among alternative paths and the ultimate economic issues at stake? First, positive externalities. Even in a "path-independent" process, externalities cause a discrete divergence between a theoretical social optimum and a realized equilibrium, a divergence quantifiable in relation to the difference between private and social costs and benefits. In a path-dependent process, externalities can result in the selection of a whole different path, and the original divergence can in a certain sense be greatly magnified. Of course, to the extent that externalities are internalized, as assumed by Liebowitz and Margolis (1994, 1995), this divergence disappears. In practice, however, externalities are rarely if ever fully—or perhaps even mostly—internalizable, and the presumption remains that uninternalized externalities could be a substantial factor in the onset—as well as in the continued local stability—of a path dependent process.[3]

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[3]Liebowitz' and Margolis' (1994, 1995) general response concerning the role of externalities in path dependence is that any inability to internalize externalities can be characterized as the result of transactions costs, so that the path taken represents the most efficient one known and attainable, once all costs are taken into consideration. Granting the partial validity of this argument, it remains the case that potential paths may differ in their foreseeable relative efficiency by an amount within the range of the perhaps considerable transactions costs required to direct the emergent collective choice to the (expected) most efficient outcome. Furthermore, the argument does not address either the implications of lack of foresight or cases where the issue at stake is not Pareto efficiency but rather the distribution of rewards. What is problematic in Liebowitz'

Second, and in most cases more importantly, the selection among paths may take insufficient account of the issues at stake because agents do not know enough to foresee the consequences of their choices—either the destinations of diverging paths or how their choices can best assure the realization of desired outcomes. Agents may, for example, have uncertain or mistaken views about the relative advantages of different new techniques or about other agents' interests, or they may not foresee such later emerging factors as the benefits of technical standardization and thus the tendency of a de facto standard to emerge. Importantly, this applies not only to the possible selection of an inefficient rather than (Pareto) efficient path, but also to the selection among alternative Pareto-efficient paths that generate different payoffs for different agents.

These two factors, especially foresight, are what distinguishes path dependence from the fulfilled-expectations processes that in some models determine allocation when network externalities are present. Let us suppose—quite counterfactually—the existence of perfect, complete intertemporal markets, with complete information about technological possibilities (which may nevertheless be time dependent) and agents' interests and preferences. In this case the optimal path (or set of Pareto-optimal paths) is clear to all agents; furthermore, all externalities can be internalized. Future markets clear at time zero, leaving no deciding role for the dynamics of the process as such, and thus there is no path dependence. When all objects of future choice (and their consequences) are known and thus "present" at the beginning of an allocation process, and when the externalities of agents' choices are internalized, then the path itself becomes an object of choice for the internalizing, optimizing agent—precisely David's (1988, 1997) criterion for what he calls "moderate to mild history," as opposed to the "strong history" of path dependence. There may still be multiple potential Pareto-optimal equilibria as a result of increasing returns, but the selection among these takes place through some process of formation of rational (and subsequently fulfilled) expectations, perhaps assisted by the preemptive actions of (externality-internalizing) agents who have a

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and Margolis' discussion of externalities is not their analysis of the impact of transactions costs on behavior but rather their assertion that a process that is not inefficient by their criteria is uninteresting and not at variance with "the neoclassical model of relentlessly rational behavior leading to efficient, and therefore predictable, outcomes" (Liebowitz and Margolis, 1995).

stake in which Pareto-optimal equilibrium is selected (Katz and Shapiro, 1985).

However, a world in which information about the characteristics and uses of new technologies and the interests and strategies of agents is progressively revealed, not foreseen from the beginning, is one in which the path of allocation as such is not an object of choice for any agent and the end result of an allocation process may be decided by its particular history. As this is certainly the sort of world in which we live, Paul Krugman (1998) is unwarranted in criticizing Arthur for not basing his models on fulfilled expectations (in contrasts to Krugman's own models of increasing returns yielding multiple equilibria).

In a world of imperfect foresight, path dependence arises whether or not externalities are fully internalized as they arise. What of a world—unrealistic, to be sure—of "perfect" foresight but incomplete internalization? If we stipulate that only fundamental factors but not contingent events are foreseen, and if it is precisely the externalities associated with these events that are not internalized, and if these events and their effects are "large" enough to prevent the formation of fulfillable expectations, then the path of allocation is not an object of choice at the beginning, and path dependence is possible.

Fulfilled-expectations processes also involve positive feedbacks and have a certain continuity with path-dependent processes. In fact, those who model such processes implicitly assume a certain period of uncertainty during the process of expectation formation, a period during which both suppliers and users of competing techniques seek to understand and influence the process (Katz and Shapiro, 1994; Besen and Farrell, 1994). During this period the process is path dependent, as agents consider various outcomes possible and form their expectations in response to the ensemble of each others' contingent actions.

The consequences of imperfect foresight and imperfect internalizability are similar whether the system-level issue at stake is potential inefficiency or, rather, which of two or more (each Pareto-efficient) proprietary products or techniques will be established as a de facto standard. Under these conditions, future paths as such are not objects of choice at the beginning of the process for interested agents, individually or collectively. The competition is not decided at one point in time by a Katz-Shapiro (1985) mechanism; it is decided over time, path-dependently. This does not, of course, rule out strategic behavior—quite the contrary. If the sponsors of the alternative techniques recognize that the allocation process is a path-dependent one with positive feedbacks, they act strategically to influence the early events that have a disproportional impact on the subsequent evolution of the process. They promote their proprietary system “architectures” in the manner described by Morris and Ferguson (1993). As those authors point out, such behavior is pervasive in advanced-technology industries.

It is curious that Liebowitz and Margolis regard such purposeful behavior as the antithesis to path dependence rather than as presupposing it.[4] There appear to be two reasons for this. First, early papers on path dependence emphasized how it can result from exogenous “historical accidents” in contexts where there is no purposeful sponsorship of competing techniques. Second, Liebowitz and Margolis (1995) confuse the concept of path dependence with the mechanistic, deterministic models of chaos theory or “sensitive dependence on initial conditions”—even though promoters of the concept of path dependence have deliberately avoided this association. Thus Liebowitz and Margolis argue that purposeful, forward-looking behavior overrides the effects of mere “accidents” or initial conditions—that economic allocation does not evolve mechanistically from the past but is rather steered by interested agents toward desired future ends. In this they surely have a point. Where they err is in never coming to terms with the positive feedbacks that interact with purposeful behavior and the limitations that history imposes on what future-oriented behavior can accomplish. When different equilibria are possible and paths as a whole are not objects of choice to interested agents, then allocation can indeed evolve in a path-dependent fashion.

## A General Analytical Framework

In order to examine, first, whether particular empirical allocation processes are path dependent and, second, the role of both network form and technological change in path dependence, I propose here an analytical framework with three features: sources of variation in agents’ choices, a source of positive feedbacks in their choices, and the possibility, in some but not all cases, of reversal of initial choices. This framework is relatively general and too informal to constitute a model, but it is applicable to a broad range of empirical cases. It

[4] Respondent Stephen E. Margolis made essentially this comment about a preliminary version of this paper presented to meetings of the Social Science History Association in October 1997.

builds upon previous rigorous modeling approaches and points the way to new ones.

### *Adopters or Users of Techniques*

There are two types of agents: (1) users and, in some cases, (2) suppliers of alternative products or techniques.[5] A typical potential user chooses the technique $T \in \{T_1, T_2, ...\}$ that maximizes either her consumption utility or the net value of a technique in productive activity. Following Arthur (1989) and others, the technique's value (in production or consumption) *V(T)* is treated as the sum of two terms,

$$V(T) = D(T) + E(T). \tag{1}$$

*D(T)* represents the user's technical valuation of the technique, based on the user's expectations about how the technique will serve either the particular tastes of the consumer or the particular productive activities of the producer; in productive activity, this term represents (discounted) expected streams of incremental net revenues or profits. This technical valuation function offers, we shall see, several ways to introduce variation into the process, and it is the chief means through which technological change can affect the process as it proceeds. The second term, *E(T)*, reflects the user's expected benefits of using the same technique as other users—the expected present value of network integration benefits or network externalities. This function is the source of positive feedbacks, and the form of this function reflects the form of value-producing network interactions among agents, as I consider in a later section.

David (1993) has called attention to the need to consider reversibility as well as irreversibility of choices, and I propose to do so by stipulating a conversion cost which is not necessarily prohibitive. The value of the technique to which one switches is then

$$V(T) = D(T) + E(T) – C(T), \tag{2}$$

where $C(T)>0$ is the cost of conversion to that technique (assumed here to be independent of which other technique was used previously). For a user's current technique, $C(T) = 0$.

It may be noted that *D(T)* is normalized differently in equation (2) than in equation (1), differing by the sunk costs of adopting technique *T*. In general, conversion costs may be

[5]I use the term "technique" (where Arthur uses technology or system variant) to refer to a particular instantiation of a more general technology. Thus, computer operating systems are a technology, while MS-DOS and Linux are techniques. The system of flanged wheels on fitted rails is a technology, while specific railway track gauges are techniques.

regarded as the portion of these sunk costs that must be paid out anew when switching from one technique to another. In the case of railway track gauge, for example, the same roadbed substructure and rolling stock can usually be used for track of different gauges, but rails have to be moved, wheel trucks altered, and sometimes locomotives replaced.

### *Suppliers or Sponsors of Techniques*

Although in some cases techniques are inherently non-proprietary—railway track gauges, for example—in many cases they are developed and sponsored by a second class of agents. Their role is to explore new technology, choose the specific features of marketed products or techniques, and then supply and promote their techniques through pricing and marketing. In pursuing research and selecting features, they may need to make guesses both about the potential for further improvements in specific techniques and about what features will best serve user needs in a yet unproven market. In their pricing and marketing behavior, they help form users' expectations both about the value of the specific technique—*D(T)*—and about the future choices of other users and thus the future value of network benefits—*E(T)* (Katz and Shapiro, 1994; Besen and Farrell, 1994; Liebowitz and Margolis, 1994, 1995). In this, they serve as partial internalizers of the externalities among users.

### *Solution Concepts*

How a model of allocation is solved depends on further assumptions. Given perfect foresight (into both technology and users' interests) and internalizability, as discussed in the previous major section, paths as a whole are objects of choice at the beginning of the process, and it is reasonable to apply models in which rational fulfilled expectations lead to a Pareto-optimal result. Such processes are not path dependent.

More realistically, given imperfect foresight, as new adopters arrive over time and choose the technique that offers the highest expected total value, both *D(T)* and *E(T)* may change in ways not perfectly predicted or controlled. Several potential sources of variation could lead to a branching of potential paths of allocation. For one, potential adopters may vary either in the objective suitability of different techniques for their purposes or in their subjective expectations about the suitability of different techniques. Arthur's (1989) well-explored stochastic arrival process considers what happens when such adopters arrive at the market sequentially in unforeseeable, random order. Market share evolves, at first, as a random walk, but when one technique gains a sufficient market share, learning or network effects override the preferences of some adopters for minority techniques, causing the process to lock-in to the technique that had gained the early lead for purely stochastic reasons.

This approach has the weakness that it does not readily lend itself to incorporating either expectations, except in a truncated form, or the sponsorship of techniques and internalization of externalities—points that Liebowitz and Margolis (1995) seized upon. Nevertheless, Arthur's more general analysis of the dynamics of positive feedbacks in market share does not depend on the specific stochastic-arrival mechanism and remains generally valid. Furthermore, I have found the stochastic-arrival mechanism to offer a good explanation for the adoption of specific railway track gauges by the earliest local railways in various regions (Puffert, 2000, 2001a).

Another reason to look beyond the stochastic-arrival mechanism is that stochastic variations in adopter arrival are likely to be weak in cases where numerous adopters make simultaneous choices—and other potential sources of variation are likely to be much stronger. Most important, I believe, are the contingent aspects of the behavior of suppliers, particularly their decisions concerning what lines of research and development to pursue, what features to include in their products or techniques, and how to market their techniques. As Nelson and Winter (1977) have taught us, firms do not follow known recipes for maximizing profits but rather engage in exploratory behavior, particularly in the context of unproven technology and untested market interest. A range of behavior is possible, some strategies succeed better than others, and, given increasing returns to adoption, variations in behavior may easily be sufficient to set an allocation process on one path rather than another. I am developing a model to explore such an allocation process (Puffert, 2001b).

Adopters also live in a world of uncertainty, and their expectations may well be influenced both by the contingent actions of suppliers and by "exogenous" events that seem to offer information about the relative technical values and future market shares of different products or techniques. Thus, even the outcome of a single, well-publicized early typing contest may have affected the later course of allocation of keyboard systems (David, 1986; cf. Liebowitz and Margolis, 1990).

Over time, greater information is revealed about the relative value of different techniques in application, but meanwhile the allocation process has already proceeded along a specific, locally stable path. Even if the technique and path selected are shown to offer less to users than some other that had been available, the new information may offer less incentive than would be needed to overcome the local stability and redirect the process.

### Technological Change and Path Dependence

Technological change may affect the path dependence of an allocation process in several ways. First, again, it is a source of variation. The uncertainty associated with new technology and its potential uses creates room for a variety of contingent beliefs, expectations, and behaviors that together may determine which particular path an allocation process takes. Second, as Cowan (1990) has noted, particular contingent technological advances may encourage development of those advances rather than exploration of other techniques which in some cases would offer greater long-term benefits. Third, technological change may introduce new best techniques. These may be “locked out” because conversion costs (including transaction costs) outweigh possible gains, or they may offer sufficient benefits to induce conversion, rendering the old technique obsolete and ending the previous path-dependent lock-in. In a fourth effect, technological change may lead to a sort of reconvergence of different paths, at least in the sense that a technique evolves to develop features similar to those that might have developed along a different path. In terms of the analytical framework here, these first four effects all work through the technical valuation function D(T).

Fifth, technological change can reduce the level of conversion costs C(T) and thus end the local stability of an established path. Sixth and last, technological change may affect the network benefit or externality function E(T) through the introduction of adapters or “gateways” (David, 1987) that offer a substantial degree of network integration even in the absence of a common technique. Adapters are devices that enable products using one technique to function within a system or network that is based on another technique. Gateways are connections among otherwise incompatible networks, formed either by adapters or by the performance of some task that effectively converts a product or service from one technique to another. In railways, for example, rolling stock that crosses a “break of gauge” can shift to the new gauge either through adjustable wheels and axles (an adapter) or through the complete exchange of wheel trucks (a gateway operation).

## Network Form and Path Dependence

Models that examine path dependence or, more generally, network externalities often assume that network externalities (or network integration benefits) vary simply with what David (1993) calls the macro state of the system; that is, that $E(T)$ can be expressed simply as $E(N(T))$, $E' > 0$, where $N(T)$ is the number of adopters (or, alternatively, market share) of technique $T$. As David notes, this is often inappropriate, and he proposes, as an alternative, the assumption that agents have direct value-producing interactions only with their immediate neighbors on a one- or two-dimensional lattice. Here we consider also a larger set of network forms that arise in concrete empirical cases.

In general, the network externalities or network integration benefits for each agent $i$ depend on her specific value-producing interactions with other agents, that is, on both the graph $\boldsymbol{\Gamma}$ representing these interactions and, perhaps, on the agent’s position within that graph:

$$E_i(T_i) = E_i(\boldsymbol{\Gamma}(\mathbf{T}_{\grave{i}}, T_i)), \tag{3}$$

where $T_i$ is the technique chosen by $i$ and $\boldsymbol{T}_{\grave{i}}$ is the vector of techniques chosen by agents other than $i$. Both the dynamics of the allocation process and features of its outcomes depend on the specific graphical structure. The various possible network structures may involve either direct interactions among users or else interactions through providers of “network services” (figure 1). The following discussion assumes that all potential value-producing interactions are of equal value.

### *Alternative Forms*

*Direct interactions* among users of a technique may take numerous forms, of which the following are important basic types (figure 1).

(1) A complete network structure features direct interactions (the links or "edges" in a graph) among all users (the nodes in a graph) who adopt a compatible technique. For such networks, if the values of interactions are assumed equal, then $E(T)$ takes the form $E(N(T))$.

(2) A *random* network structure involves defined ex ante probabilities of interactions among pairs of users. If these probabilities are equal for all links, then functional form $E(N(T))$ again applies.

(3) *Spatial* networks involve direct links only among immediate neighbors, most simply modeled as within a regular lattice. In many empirical examples, there are also economically relevant indirect links with the neighbors' neighbors (and so on), so that the broader "connectivity" of the network is also relevant. For example, local railway lines have an interest in the ability to exchange traffic both with immediate neighbors and indirectly with more distant railways. As different agents have different neighbors, function $E_i(\boldsymbol{\Gamma}(\boldsymbol{T}_{\grave{\imath}},T_i))$ varies among agents and may take a relatively complicated form.

(4) When potential interactions occur only within unconnected or *discrete subnetworks*, with complete or random links within the subnetworks, function $E_i(\boldsymbol{\Gamma}(\boldsymbol{T}_{\grave{\imath}},T_i))$ depends only on the number of other users within the user's subnetwork that use the same technique. Whether users in other subnetworks use the same technique does not matter.

(5) *Overlapping subnetworks* are similar to the foregoing in terms of the structure of each agent's incentives, but agents who potentially interact with each other differ in the sets of other agents with whom they could have interactions. Spatial networks in which only direct interactions matter are a subset of this network form and offer a simplified modeling approach.

(6) *Complementary groups* consist of agents possessing complementary components of some larger production system, who each therefore have potential value-producing interactions only with the other group. The paradigm for this network form is the set of trained typists together with the set of firms who buy typewriters and hire typists to use them (David, 1985), which may be regarded as a special case of either of two sorts of networks

discussed by Economides (1996): first, the supply network of firms or agents in upstream and downstream industries and, second, buyers and sellers in markets where both gain from increasing market “thickness.” In different contexts, members of one group may have potential interactions with all or with only some of the members of the complementary group, and the resulting overall form could be either densely interconnected or divided into subnetworks.

(7) For each of the foregoing network forms, value-producing interactions could be either reciprocal or one-way. An important example of a one-way effect is a *sequential learning* process in which later adopters of a technique have an opportunity to adopt a less expensive or improved version as a result, respectively, of learning-by-doing in the production of earlier versions or learning-by-using in their application. Each adopter in this case benefits from, or “interacts” with, previous adopters only. Arthur (1989) motivated his basic model of path-dependent allocation by considering just such an effect. It is noteworthy here that supply-side learning effects can, like demand-side effects, be modeled in terms of networks.

At least four important network structures are based on *indirect interactions* among users of the technique, where direct interactions are with the suppliers of network services:

(8) In the *telecommunications paradigm* (Economides, 1996), users are connected directly to service providers who in turn are connected directly both to a set of other users and also to other service providers with connections to further sets of users. Each service-provider network requires use of a common technique (for example, a specific cellular or wireline analog or digital standard), but connection is possible to users of other techniques and other service providers, although often at a greater cost or price. Interconnections among “local” networks are provided by gateways, so that a common user technique is not needed.

(9) In the *broadcast paradigm*, network interactions are one-way from service providers to users, whose receivers must be compatible with broadcast signals. Given that users receive signals from multiple broadcasters, it is advantageous that these all use the same technique. Broadcasters also often gain revenues from having more viewers or listeners.

(10) In the *software paradigm*, there is monopolistic competition among suppliers of application software for specific hardware platforms or operating systems—for example, for computers or video players. As a result, both the variety and price of software improve for each user as the total number of users increases, making the hardware platform or operating system more valuable. The value of network interactions for each user may, for example, take the form $E(M(N(T))$, where $M$ is the number of software suppliers. This functional form reduces to $E(N(T))$, and the network form itself can therefore be regarded as collapsing to form (1). In cases where different sets of agents use different application software, the network form may collapse to (4) or (5).

The relevant feature of software is that, as pure information content combined with a low-cost distribution medium, it exhibits high fixed costs and low variable costs, giving rise to strong economies of scale. The network externalities in this case are not technological but rather pecuniary in nature, and Liebowitz and Margolis (1994) have asserted and attempted to demonstrate that the externalities therefore have no effect on the nature of the allocation process, based in part on the quixotic assumption that all software-supplier rents can be internalized by the sponsor of a technique (the supplier of the hardware or operating system).[6] However, as Krugman (1991) points out, "In competitive general equilibrium, of course, pecuniary externalities have no welfare significance and could not lead to ... interesting dynamics.... In the presence of imperfect competition and increasing returns, pecuniary externalities matter; for example, if one firm's actions affect the demand for the product of another firm whose price exceeds marginal cost, this is as much a 'real' externality as if one firm's research and development spills over into the general knowledge pool."

(11) Finally, learning effects may be mediated by the suppliers of techniques that are subject to learning. Nevertheless, the network form can be regarded for some purposes as collapsing to that of form 7.

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[6]Moreover, Liebowitz and Margolis asserted that network externalities are generally pecuniary rather than technological in nature. This is simply false, as the examples in this paper show.

### *Implications of Network Form*

The main implication of network form for an allocation process is that positive feedbacks are not always based simply on the macro state of the process. Sometimes they are, as for network forms 1, 2, 7, and perhaps 10, and in such cases the choices of new adopters tend to reinforce any asymmetries in total market share. If economically relevant network interactions take place only in discrete subnetworks (form 4), then positive feedbacks take place only within these subnetworks. Indeed, if only a small number of agents are involved and these already directly communicate with each other, then they can simply coordinate their choices by agreement before adopting a technique. Extended families can adopt the same videorecording system in order to exchange home videos, and co-authors can adopt common word-processing software (Liebowitz and Margolis, 1994).

Much more often, however, subnetwork interactions take place among overlapping subnetworks, whether spatial (form 3) or otherwise (form 5). In these cases, an interesting dynamic may develop, as I (Puffert, 2000, 2001a) have both modeled and documented empirically in the case of railway track gauge. Early adopters in an allocation process coordinate their choices "locally" (to use the spatial metaphor also for non-spatial cases), but different techniques may be adopted in different locations. Later adopters use the same technique as adjacent established users, leading to the expansion of regional networks of a common technique. Eventually, regions using different techniques run into each other, so that agents on the borders of these regions cannot adopt the same technique as all potential partners in interaction. Local standard techniques emerge, but a "global" (or continental) standard does not. If indirect as well as direct connections among agents matter, as in the case of railways, then all agents pay a price for the resulting diversity. Of course, given perfect foresight and complete internalization of externalities, all agents will coordinate their actions from the start (unless diversity is in fact efficient due to differences among users in which technique suits their needs). Empirically, however, both factors are often lacking in the crucial early stages of an allocation process.

The emergence of diversity in a spatial network (or any network of overlapping subnetworks) raises the issue of conversion in a way that does not arise when feedbacks from the macro state of the system lead to global standardization from the start. David (1993) and co-authors (David and Foray, 1993; David et al., 1998) examine the case where agents on the borders among regions of common technique may change their technique randomly to that of one or another neighbor, as might happen when network interactions are random and conversion is costless. This enables them to draw on the extensively developed theory of Markov random fields or interacting particle systems. I examine the case where conversions have a cost and depend deterministically on systematic network interactions. Both approaches show how conversion can yield increasing coordination over time, possibly but not necessarily eliminating early diversity. My approach also demonstrates how various schemes for the internalization of externalities—for sharing the costs of conversion—can contribute to the resolution of diversity, providing that transactions costs are sufficiently low (Puffert, 2001a). It also demonstrates that permanent or even temporary diversity, and thus unrealized network integration benefits, can be a greater source of inefficiency in an allocation process than selection of a "wrong" technique.

The consideration of network forms also clarifies where adoption of a common technique matters most for the facilitation of network interactions, and where gateways and adapters render complete standardization less important. Both in the telecommunications and broadcast paradigms (forms 8 and 9), users must adopt the same technique as their service provider(s), but not necessarily the same technique as all other users. In telecommunications, network-level gateways enable users of different service providers to interact. Broadcasters can, at relatively low cost, convert programming developed in one format to their own format. Broadcast receivers can also be made for multiple formats, as has long been the case for radios and is increasingly so for televisions, particularly in combining digital satellite and high-definition capabilities with analog. Gateways can also link spatial subnetworks together, at costs that may be low enough to effectively unify the networks, as in the case of electrical power distribution, or not, as in the case of railway track gauge.

Network form also has implications, not yet extensively explored, for the extent to which network externalities can be internalized, either by the sponsors of techniques or by coalitions of users. As noted, users in small, discrete subnetworks can readily coordinate their choices, but a large number of users in overlapping subnetworks may not be able to do so. A network-form-based theory of transactions costs could yield more specific, testable propositions. The supplier of a technique subject to learning (form 11) is naturally able to internalize the benefits of learning, including by pricing early versions of a technique below cost in order to increase sales and reduce the cost of later versions.

## Case Studies

The value of these considerations can be seen concretely in a sampling of empirical cases representing different network forms and different characteristics of technology (table 1).

Railways form spatial networks in which standardization of track gauge facilitates the exchange of traffic among companies or state administrations (Puffert, 2000, 2001a). Early in the history of railways, diversity in gauge emerged in numerous regions both due to uncertainty and changing opinions about optimal gauge and also due to lack of foresight into the later importance of long-distance network integration, as early railways usually served strictly local transport needs. Although the diffusion of specific engineering traditions limited the proliferation of gauges, six gauges gained widespread adoption in North America, seven or more became regional standards in Europe, and multiple gauges were introduced to all other continents and to numerous specific countries. The introduction of specific gauges to specific regions was essentially a stochastic arrival process, as gauges were chosen by engineers and promoters representing random draws from a heterogeneous population.

Nearly all the diversity of gauge in North America and much of that in Europe were later resolved as demand grew for long-distance transport. This was sometimes facilitated by side-payments, interregional system-building, and coordination—practices that internalized the mutual externalities of local railways. Costly diversity remains in Australia, in India, at the border of France with Spain, and numerous other places. A variety of gateway techniques (e.g., mixed-gauge track and exchangeable wheel trucks) have offered a degree of network integration despite diversity and have also sometimes facilitated long processes of conversion, providing a "migration path." Most railway engineers regard the common 4'8.5" (1435 mm.) gauge, adapted from the gauge of small coal carts in mines near Newcastle and used today on nearly 60 percent of world railways, as narrower than optimal, but the main source of inefficiency in the process of gauge selection has been the emergence and persistence of diversity.

Adoption of a common technique has mattered less for railway electrification networks (Puffert 1993a, 1994a), because railways have usually preferred to change locomotives at (national or company) borders anyway. Nevertheless, recent efforts to achieve a "Europe without frontiers," particularly in high-speed train service, have increased the cost of diversity. The development of relatively efficient adapters in multi-current locomotives and high-speed trainsets is bringing improvements in network integration.

Early industrial and household electrical power distribution networks were marked by an initially vigorous competition between Edison's direct-current (DC) and Westinghouse's alternating-current (AC) systems, as each promoter's strategy responded both to network effects and to a series of technological innovations (David and Bunn, 1988; David, 1990). Development of an inexpensive gateway technique, the rotary converter, provided a means to join together local subnetworks of each system, enabling end users to adopt the systems best suited to their needs and facilitating the progressive replacement of DC by AC in the trunk distribution system, where the advantages of AC proved substantial. Technological change broke the allocation process free of its early history, making it path independent—although the persistence of a variety of local-standard AC frequencies and voltages has certainly been path dependent. The process of rationalization was facilitated in the end by externality-internalizing cooperation between Edison's and Westinghouse's firms.

Television broadcasting has heretofore required local standards so that viewers could readily receive signals from different broadcasters, but broadcasters have been able to use signal converters to adapt programming from different formats. Adapters and multi-system receivers for users can now receive both analog signals and digital signals from satellites and terrestrial high-definition television (HDTV) broadcasters. Standards have been selected by national authorities, in several cases with a view to industrial policy based partly on learning effects. France and Germany introduced the SECAM and PAL color television standards, respectively, rather than adopt the North American NTSC system, in part to reduce the advantage of experienced U.S. equipment manufacturers. Japanese government and equipment manufacturers developed their analog HiVision HDTV system during the 1980s in an effort to take the lead in HDTV, hoping to establish a global standard that they would dominate. Europeans responded with their own system, HD-MAC. Both systems, however, were rendered obsolete during the 1990s by development in the United States of a digital HDTV system. Japan and Europe have subsequently adopted variants of the U.S. standard. Thus, technological change overcame efforts to preemptively determine new standards.

This new technology may well overcome the historical legacy in much of the world. First, however, program developers, broadcasters, and viewers must overcome the chicken-and-egg dilemma of each waiting to be sure that others will adopt before they lay out the initially high cost of equipment. The transactions cost of overcoming this dilemma by organizing a simultaneous adoption appear to be high. The dilemma may be resolved, however, by new digital technology, as digital HDTV shares video compression and audio technology with other recently developed consumer electronics products, and it readily interfaces with computers as well. Consumers may therefore buy HDTV receivers as relatively low-cost additions to home-entertainment or information systems even before there is large-scale transmission of HDTV signals. Early HDTV studios and broadcasters may reach threshold numbers of viewers by relying on cable and satellite transmission.

Cellular telephony requires a common technique for a given service provider, but network-level gateways offer connections to other cellular and wireline telephone users, and multi-system handsets facilitate user “roaming” in areas of different service providers. Thus, there has been no path-dependent obstacle to the introduction of rapidly improving new techniques. There is path dependence, however, in competition among alternative techniques for adoption by service providers and regulators, as learning effects reduce the costs and improve the capabilities of both network equipment and handsets (Puffert, 1993b).

The Internet is a network of networks—of numerous local area and wide area electronic data networks that use a variety of architectures and signal protocols. These are linked to the Internet and thus to each other by means of signal-protocol converters or “gateways”—a term first applied to technical standards in this context.[7] The Internet may be regarded as the network interlinking the hub nodes within the telecommunications paradigm (form 8). After the early development of data-communications networks based on proprietary architectures (primarily those of IBM and DEC), two efforts were undertaken to develop vendor-independent suites of standards. One, based on the Transmission Control Protocol / Internet Protocol (TCP/IP) developed incrementally for the now widespread Internet. Over much the same period, international standards-development organizations sponsored the definition, by computer scientists, of an alternative, much more comprehensive suite of standards known as the Open Systems Interconnection (OSI) model.[8] Although OSI has numerous theoretical advantages over TCP/IP, it has gained little acceptance in the market. Equipment and software suppliers have found it easier to develop and test products within a functioning network and standards environment, while network users have not wished to purchase products based on untested concepts. A decade ago, experts debated whether TCP/IP and OSI internets would function in parallel during a period of transition to OSI or whether TCP/IP would evolve by incorporating OSI concepts that extend TCP/IP's capabilities in ways particularly demanded by users ("Great OSI Debate," 1992). The latter has proven to be the case. The capacity of the TCP/IP technique to evolve, and thus converge in some respects to the OSI model, have brought the allocation path to a point, in some but not all dimensions of technology, that might have been reached along other possible paths.

Markets for magnetic and optical recording and reproducing technologies for audio, video, and data involve at least three sorts of network interactions: direct exchange of software among users (within discrete or overlapping subnetworks); software-supply effects both in sales and rental markets; and learning effects by system-equipment suppliers, giving rise to reduced costs and improved features (Puffert, 1994b). Suppliers' foresight into the

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[7]According to a standard industry reference (VLSI Research, 1988, p. xxi), a gateway is "a particular type of equipment used to connect incompatible networks by means of a protocol translator." David (1987) brought the term into general use for technical standards. The term was also applied to railways in an otherwise unremarkable 1986 seminar paper by the present author.

[8]The OSI project received much of its impetus from European firms and governments seeking to reduce the competitive advantage of U.S. firms that promoted their proprietary architectures. The more modest TCP/IP project was designed simply to interconnect networks using different architectures.

tendency for competitive exclusion in the setting of de facto standards have led them to unite in supporting common standards for such technologies as first-generation compact discs (CDs and CD-ROMs) and second-generation DVDs (digital versatile discs), forming common expectations and effectively choosing the path of allocation at the outset of the process. DVD equipment has been made backward-compatible for current CDs and CD-ROMs (it has built-in adapters), reducing the cost to consumers of migration to the new technique and eliminating any tendency for the market to remain locked in to the older technique.

Foresight has not always preempted path-dependent allocation processes in this industry. The most celebrated systems competition was that among systems for consumer video recording—primarily Sony's Betamax system and JVC's VHS—from the mid-1970s to mid-1980s. Arthur (1994) explained this as the result of positive feedbacks in the video film rental market, as video rental stores stocked more film titles for the system with a larger user base, and new adopters chose the system for which they could rent more videos. However, Cusumano et al. (1992) showed that this effect, although important, emerged at only a late stage in the competition, when VHS already had a strong lead. Nevertheless, they argued that the earlier process already had a path-dependent market-share dynamic, because an increasing number of manufacturers and distributors supported VHS over Betamax as they came to believe that VHS would emerge as a de facto standard. Three contingent early differences in strategy were crucial. First, Sony proceeded without major co-sponsors for its Betamax system, while JVC shared VHS with several major competitors. Second, the VHS consortium quickly installed a large manufacturing capacity. Third, Sony opted for a more compact videocassette, while JVC chose instead a longer playing time for VHS, which proved more important to many customers. In a contrasting interpretation, Liebowitz and Margolis (1995) treated this playing-time advantage for VHS as the single crucial factor in the competition, so that VHS won because its features more closely matched consumer demand—and not due to path dependence. When, however, one views the strategic choices of firms as a source of contingent variation that affects the subsequent course of allocation, it becomes clear that the process was indeed path dependent.

Microcomputer operating systems offer one of the more topical cases among those discussed here, as rapid changes in technology, in markets, and perhaps in the institutional environment continue to affect the course of allocation. Although observers' attention has turned increasingly to the future prospects of Linux and the open-systems movement, the most notable systems competition thus far has been that between Apple's Macintosh OS, supplied together with a hardware system at a high unit mark-up, and Microsoft's MS-DOS and Windows, available for a wide range of third-party hardware at what was initially a low unit price. Apple followed a traditional business model in maximizing current profits (Solman, 1996), while Microsoft's strategy showed greater foresight into the effects of positive feedbacks. During the 1980s and early 1990s, Microsoft's strategy gave it a lead in market share that in turn stimulated a greater supply of application software, increasing the relative value of the Microsoft systems to users. Many users (and programmers) nonetheless preferred the graphical user interface of Macintosh, but the introduction of Windows 95 largely matched most of the features in which Macintosh had held an advantage, and Apple's share of the market then began to decline markedly.

The Macintosh OS maintained a lead for a time in high-end graphics applications, educational software, and other market niches where either it had gained an early lead or else its tighter technical integration between graphical user interface, operating system, and hardware gave it a particular advantage. These market niches have constituted subnetworks in which users' interactions with each other have had a greater value than their interactions with the larger user community. Nevertheless, the overlapping of user subnetworks for different applications (network form 5 or 3) has facilitated the expansion of the Windows-standard "territory" into "regions" previously dominated by Macintosh. Apple's strategy for survival relies partly on gateways between Macintosh and Windows, facilitated both by Windows emulators (i.e., adapters) running on Macintosh and by the development of similar versions of some application software for both systems. The emulators cannot match the performance of Windows machines, however, and much application software is available only for Windows. Apple's strategy relies as well on innovation, most visible recently in iMac hardware and operating system version OS X, designed to exploit new, network-interactive market segments. Apple has also developed application-software-development tools that, the company claims, reduce the cost of developing software ten-fold. If true, this could alter the software-paradigm feedback mechanism strongly to Apple's advantage.

Learning effects have been the principle source of path dependence in the adoption of nuclear power techniques (Cowan, 1990). The dominant "light-water" reactor design appears to be inherently less efficient than potential alternatives, but it was rushed into use because the Cold-War political value of peaceful uses for nuclear technology overrode the value of finding the most cost-effective technique. Thereafter, engineering experience for the light-water technique continued to make it the rational choice for new reactors over less well developed alternative designs, although equal development of the alternatives might have made them superior. The principle U.S. suppliers and sponsors of light-water reactors, Westinghouse and General Electric, acted as internalizers of externalities by offering early systems at prices below cost in order to gain experience and offer improved systems to later adopters at higher prices.

Both local positive feedbacks and learning effects have affected farmers' choices between systems of chemical pest control and integrated pest management (IPM) (Cowan and Gunby, 1996). IPM relies in part on predatory insects to devour harmful ones, and the drift of chemical pesticides from neighboring fields often makes the use of IPM impossible. Predatory insects also drift among fields, further raising farmers' incentives to use the same techniques as neighbors. To be practical, IPM must be used on the whole set of farms that are in proximity to even one other in the set—that is, the larger network made up of the overlapping subnetworks that are subject to drifting pesticides. Where this set is large, the transactions costs of persuading all farmers to forego chemical methods are often prohibitive. Adoption of IPM has also depended on learning, both at the global level and locally. The path-dependent local lock-in of both techniques has sometimes been upset by such developments as invasions by new pests and the emergence of resistance to pesticides.

Finally, the disputed case of early typewriter keyboard systems is ripe for further examination in light of issues raised here. David (1985, 1986) argued that typists, their third-party teachers, and their employers each choose systems based on the potential pool of matches in a densely interconnected network (figure 1, form 6), generating market-wide positive feedbacks. By contrast, Liebowitz and Margolis (1990) cite instances where externality-internalizing typewriter suppliers offered in-house training to purchasers of alternative keyboards, and they implicitly deny that typists would have cared about the systems used by other potential employers. They assume a discrete-subnetwork form of interaction. Further research could clarify the relative prevalence of different mechanisms in the early employment market for typists, and thus the form of the overall virtual network and the scope and effect of positive feedbacks. Furthermore, Liebowitz and Margolis argue that the purposeful behavior of typewriter suppliers overrode the effects of contingent events. If, however, the existence of positive feedbacks is confirmed, then the relevant question is, rather, how both purposeful behavior and other contingent events interacted with the underlying dynamic of the process. The full story of the emergence of the QWERTY standard is clearly more complicated than either the story thread pursued by David or that pursued by Liebowitz and Margolis. David's essential explanation is likely more robust, however, to the presence of multiple mechanisms in the employment market.

## Concluding Remarks

The positive feedbacks that give rise to path-dependent processes of economic allocation arise because agents derive increasing value from an increasing number of interactions with other agents. These interactions often depend on the adoption of some common technique, and they either arise out of literal networks or can be treated as arising out of virtual networks. Different network forms affect the dynamic of allocation in different ways, giving rise to general standardization or creating diversity among regions or subnetworks.

Technological change may affect either the network-independent values of alternative techniques, or the extent to which value-producing interactions depend on the adoption of a common technique, or the cost of conversion. Each of these possibilities affects how the allocation process evolves, and how easily it breaks free of its past. Because new technologies and their uses—as well as the interests and strategies of interacting agents—are revealed progressively over time, allocation processes also evolve progressively rather than being decided in one timeless moment of expectations formation. The economics of path dependence tells us not only how *history* matters in allocation; it also tells us how, even more fundamentally, *time* matters.

The case studies examined here establish two facts that have often been neglected in previous studies. First, allocation processes driven by network integration benefits often lead not to a single "global" standard but rather to multiple regional or subnetwork standards. In the context of some network forms and some technologies, these subnetworks are natural market niches; in other contexts, subnetworks defined by common techniques arise as path-dependent artifacts of contingent events. Second, subnetworks based on different techniques are quite often integrated with each other by means of gateways. In some networks—e.g., for telecommunications or electrical power supply—this integration is close to perfect; in other networks—based, for example, on common railway gauges or computer operating systems—gateways offer only a relatively imperfect and costly integration.

The persistence of diversity among subnetworks raises new questions regarding efficiency: Might this diversity offer greater scope for development of different techniques, allowing the best technique to emerge, prove itself, and ultimately win the whole market? In cases where one technique does eventually win the whole market, is the selected technique the winner of a market test—or is it the path-dependent result of earlier contingent events? I have shown the latter explanation to be correct in the case of railway track gauge (Puffert 2000, 2001a), but further research may identify cases where early diversity facilitated the emergence of a more optimal technique than early standardization would have done.

The case studies also demonstrate the prevalence of behaviors that partially internalize externalities. In cases where early foresight was good—e.g. the introduction of CDs and DVDs—these behaviors selected outcomes preemptively, short-circuiting any tendency for the emergence of path-dependent competition. In other cases, these behaviors entered into later stages of path-dependent processes, rationalizing the outcomes somewhat but not leading to outcomes that were independent of earlier contingent events and paths.

Paul David's and Brian Arthur's assertions of the importance of path dependence thus withstand the critique of Liebowitz and Margolis, but the positive insights of these critics lead to a fuller understanding of when and how economic allocation is path dependent. Our understanding is also improved through taxonomies, first, of the network forms that characterize the value-producing interactions among agents and, second, of the aspects of technological change that in various ways affect the emergence and stability of alternative paths of allocation. Taking these considerations into account opens up a richer set of dynamic processes affecting economic allocation, showing in new ways how "history matters." More research is needed to gain analytical control over the various possibilities and to see how frequently they each arise in the real world.

Path-dependent processes of change in matters other than technology are also, I would hypothesize, the result of value-producing interactions among agents. Institutions, organizations, cultures, and subcultures, for example (David, 1994), all consist in interactions—interactions that have particular network forms and that depend on use of common practices or "techniques": languages and jargons, symbols, rules and norms, and more. Like path-dependent technological change, the evolution of institutions, organizations, and cultures surely depends on the pattern of interactions (i.e., the form or structure of social networks), the characteristics of innovative practices, foresight, switching costs, possibilities for internalizing external gains from switching, and other matters analogous to those discussed here.

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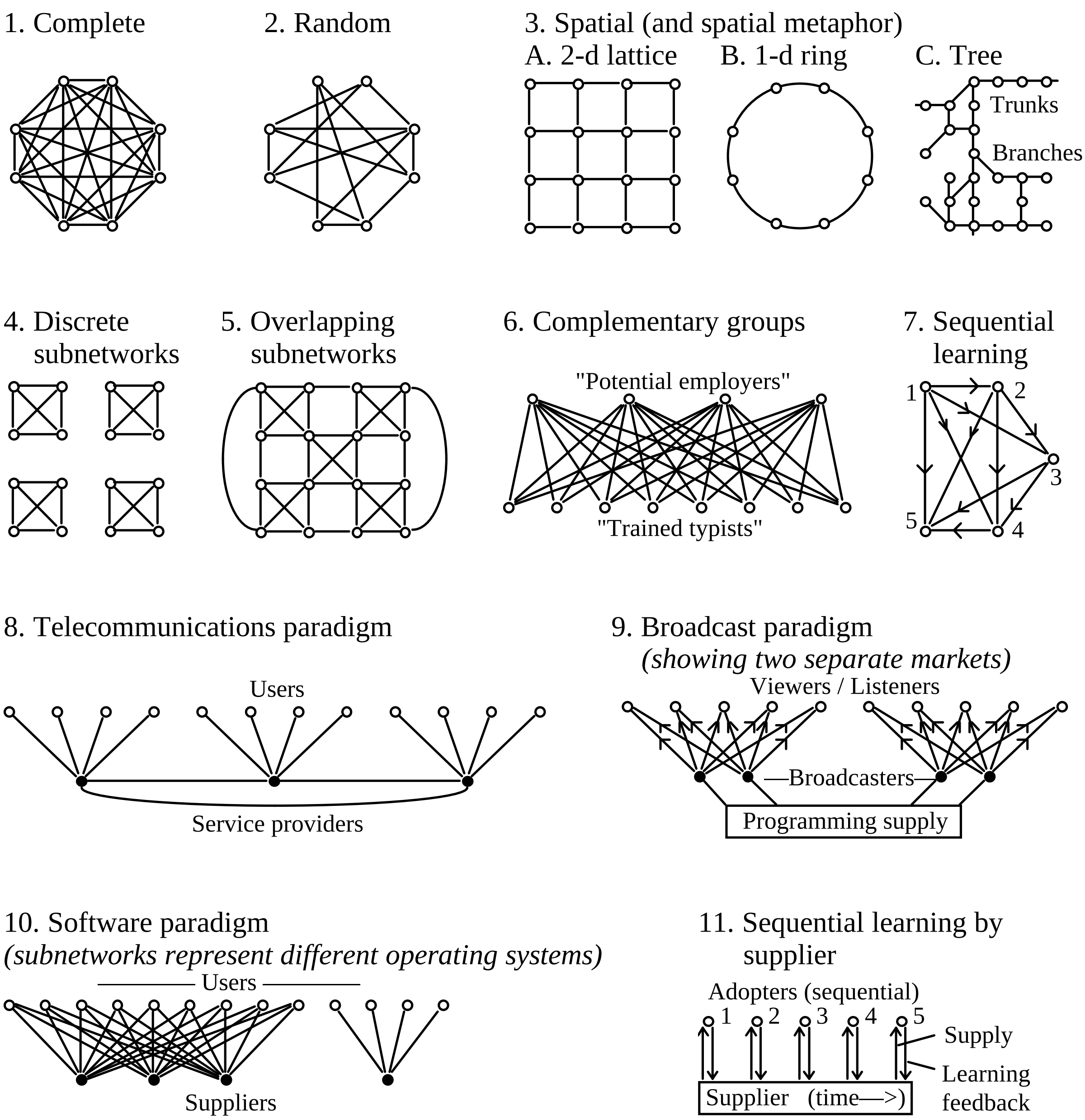
## Table 1. Features of network technologies

| Technology (selected specific techniques) | Network characteristics: Form or graphic structure | Interactions: Nature or source | Interactions: Fore-seen? | Locus of adapters / gateways | Characteristics of technology and technological change | Internalization of externalities |
|---|---|---|---|---|---|---|
| Railway track gauge (4'8.5", 5'0", 5'3", 5'6", 750 mm., 1000 mm.) | Spatial (tree) | Traffic (car) exchange | Early: often not | Users (cars) & network | Heterogeneity & change in preferred practice<br>Variety of gateways | By users; facilitated conversion |
| Railway electrification (AC 16.67 Hz 15 kV, DC 1500 V, etc.) | Spatial (tree) | Trainset & locomotive exchange | (Not an early issue) | Users (trainsets & locomotives) | Changes in preferred practice<br>Recent good adapters | Little |
| Electrical power distribution (AC/DC, 50/60 Hz, 110/220/other voltages) | Spatial (tree) | Power trans-mission | Relatively early | Network (and some users) | Heterogeneous users<br>Very efficient adapter | Supplier cooperation |
| Color television (NTSC, SECAM, PAL, HiVision, HD-MAC, U.S. & other digital) | Broadcast discrete subnet-works | Signal reception | Yes (to extent that it matter) | Network (broad-casters) & some users | New digital technology renders older obsolete | Coopera-tion in setting standards |
| Cellular telephony (AMPS, TACS, NMT, GSM, TDMA, CDMA) | Telecom subnets[1]<br>Learning | Signal exchange<br>Learning | Yes (to extent matter) | Network, users (for roaming) | Rapid innovation<br>Digital superseded original analog | Coop'n in setting standards |
| Internet (data telecom) (TCP/IP v. OSI) | Telecom interlink | Data exchange | Yes | Users and network | Rapid innovation<br>Evolvable, convergent | Coop'n in standards |
| Magnetic & optical recording & reproduction (VHS, Beta, CD[-ROM], DVD, audio cassette, DAT, DCC, MD) | -Software complete<br>-Overlap subnets<br>-Learning | -Software sale/rental<br>-Media exchange<br>-Learning | Yes or mostly | Users | Series of new products and media; digital now replacing analog | Promotion, Coopera-tion in setting standards |
| Microcomputer operating systems (MS-DOS, Macintosh, Windows, Unix, Linux) | -Software subnets<br>-Subnets | -Software market<br>-File exchange | Varied | Users | Rapid technological and market change<br>Evolvable, convergent | Promotion<br>User co-ordination |
| Nuclear power systems (light water, gas graphite) | Learning | Supplier learning | Some | None | Early uncertainty<br>High development cost | By system suppliers |
| Pest (insect) control (pesticides, integrated pest management) | Spatial<br>Learning | -Spillover of medium<br>-Learning | Yes | None | Changing pest environment (species, resistance) | User co-ordination |
| Typewriter keyboards (QWERTY, Ideal, DSK) | Comple-mentary groups[2] | Produc-tion system | ?? | Users (machine) | Neurophysiological habituation of typists<br>Remappable keyboards | Supplier promotion |

Notes: [1]Networks overlap to the extent that users "roam" in other local subnetworks. [2]Whether interacting agents form small discrete subnetworks or an interconnected network is disputed.

## Figure 1. Alternative Network Forms




Note: Nodes represent agents; links represent potential value-producing interactions, which are actualized only if agents use a compatible technique—including by means of adapter or gateway, which may reduce net value of link.