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Developing Information Infrastructure: The Tension Between Standardization and Flexibility

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This article explores the tension between standardization and flexibility in information infrastructure (II). Just like other large technical systems, the geographically dispersed yet highly interconnected II becomes increasingly resistant to change. Still, II design must anticipate and prepare for changes, even substantial ones, if infrastructure is to survive. An II contains a huge number of components that alternate between standardization and change throughout their lifetimes. These components are interdependent: when one is changed, others have to remain stable, and vice versa. The article examines theoretical concepts for framing these aspects of an II. The empirical underpinning of the article is a study of two existing embryonic manifestations of II.

The theme of this article is the development of information infrastructure (II[1]). Many analysts recognize that an II will have to continue changing during its lifetime (RFC 1994a, 6; Smarr and Catlett 1992). We are particularly concerned with how II standardization processes are balanced against this anticipated and historically proven need to accommodate to as yet unknown changes and patterns of use.

Our goals are twofold. We explore how the complex, geographically dispersed and strongly interconnected II generates a strong need for stan-

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dardization and accumulates resistance against further modifications. At the same time, the system must be open to change. The article describes the contents and process of standardization of II, paying particular attention to technical and institutional mechanisms that enable and hamper the flexibility of standardization. The process unfolds dynamically as a contingent interleaving of standardizing some parts while changing others. We analyze this phenomenon and discuss its implications for concepts in science and technology studies (STS).

Two central terms, "standardization" and "flexibility," have related but distinct meanings as they are commonly employed within STS and computer science, the field primarily concerned with the development of II. In computer science, the term standardization, as it relates to II (Lehr 1992; RFC 1994a; Rose 1992), denotes the social and technical process of developing the underlying artifact related to II—namely, the standards that govern the communicative patterns. Standardization is accordingly related to STS concepts of closure, stabilization, and irreversibility (Bijker, Hughes, and Pinch 1987; Callon 1991, 1992, 1994; Misa 1992).

Within computer science, the term flexibility has a different meaning than the term "interpretative flexibility" in STS. It denotes either (a) flexibility in allowing for further changes or (b) flexibility in the pattern of use. This clarification of terms leads to a more precise statement of our concern: we explore how the standardization of II is a process that increases irreversibility and decreases interpretative flexibility of the technologies while supporting flexibility of use and openness to further changes. This aspect of II we might call "anticipated and alternating flexibility."

Our second goal is to contribute to the ongoing design processes by providing a firmer grasp of the challenges facing standardization of II. We intend to engage the current and, at times, heated debates concerning design, and not only to study historical material or to practice "modest sociology" (Law 1994, 13-14). The standardization of II is expected to have far-reaching economic, technical, and social implications (Bradley, Hausman, and Nola 1993; OECD 1991; Scott Morton 1991).

STS accounts of standardization in relation to II are relatively rare (Schmidt and Werle 1992, 325). Moreover, the existing accounts bypass the discussion of the appropriateness of STS concepts relating to standardization to this particular case (Kubicek 1992; Kubicek and Seeger 1992; Webster 1995). Some discussion of standardization of II can be found in economics but with little trace of how the process actually unfolds (Antonelli 1993; David and Greenstein 1990). Standardization is also sometimes discussed in the literature of a subfield of computer science known as "computer supported cooperative work" (CSCW). Hanseth, Thoresen, and Winner (1994) discuss the tension between local flexibility and centralized control in relation to II standards; Star and Ruhleder (1994) focus on the adoption and patterns of use.

Information Infrastructure

The notion of II is elusive, as are such basically synonymous terms like "info-bahn," "information highway," "electronic highway." II is currently receiving a considerable amount of attention from academics, politicians, and the public. This poses obvious problems when attempting to approach II in a more sober manner. Some try to define the notion explicitly. Star and Ruhleder (1994, 253) characterize it by holding that it is "fundamentally and always a relation." Sugihara (1994, 84) defines it as a "structure [that] provides. . . the public with various types of. . . information in a more operative way." McGarty (1992, 235-36) gives a rather extensive and precise definition of II with the following keywords: shareable, common, enabling, physical embodiment of an architecture, enduring, scale, and economically sustainable.

The term "II" has only recently come into wide use. It gains its rhetorical thrust from visions of the future, such as those initiated by the Gore/Clinton plans and followed up by the European Union's plan for Pan-European II. In these visions, II is presented as a means for "blazing the trail. . . to launch the information society" (Bangemann 1994, 23). The Bangemann commission proposed ten applications around which this effort should be organized within the European Union: teleworking, distance learning, university and research networks, telematics services for small and medium-sized enterprises, road traffic management, air traffic control, health care networks, electronic tendering, trans-European public administration network, and city information highways. The proposal is in line with the projects recommended by the Group of Seven (G7) in Brussels in March 1995.

Although political manifestos tend to be speculative, it is fairly safe to expect that future II will consist of an elaboration, extension, and combination of existing computer networks with associated services (Smarr and Catlett 1992). It is likely to consist of an interconnected collection of computer networks whose heterogeneity, size, and complexity will extend beyond those that exist today. New services will be established, for instance, by developing today's more experimentally motivated services like video-ondemand and electronic publishing. These new services will subsequently accumulate pressure for new development of the II to accommodate them.

A number of embryonic manifestations of the IIs already exist. For many years, we have had application-specific networks that provide services such as flight booking and bank networks supporting automatic teller machines and other economic transactions. Electronic data interchange (EDI)—that is, electronic transmission of formlike business and trade information—is another illustration of an existing technology related to II (Graham et al. 1995; Webster 1995). The rapid diffusion of World Wide Web is the basis of a general II for information exchange and of more specialized IIs implementing open electronic marketplaces in which products may be ordered, paid for, and possibly delivered (if they exist in electronic form like books, newspapers, software or stock market information).

Basic data communication technology includes communication standards and the software and hardware implementing them. In many respects, this technology comes closest to an existing, general-purpose II. Two such basic communication technologies exist: Open Systems Interconnection (OSI) and Internet[2] (Tanenbaum 1989). OSI is developed by the International Standardization Organization (ISO).

This article discusses and compares these two basic communication technologies.[3] Space constraints ban a fully systematic and comprehensive case study. Rather, we seek to give concrete illustrations and a theoretical analysis of certain essential aspects of the II phenomenon.

Standardization of II

The Role and Importance of II Standards

It has been widely accepted almost from the advent of digital communication technology that its dissemination depends on shared international standards (OECD 1991). Standards are absolutely necessary for the II to exist. To be able to communicate, partners have to use a common standard—that is, a "language," or, in more technical terms, a protocol.

Bilateral agreements between pairs of communication partners provide one alternative to international standards. This is feasible in cases in which just a few actors want to communicate. But managing a large collection of bilateral agreements is not cost-effective, or even possible, for communities sharing an infrastructure. Proprietary protocols constitute an intermediary solution between common standards and bilateral agreements. Such protocols make it possible to exchange data among computers from the same vendor, and they are typically developed by vendors such as IBM, Digital, and HP. A large part of information exchange has until now taken place within communities using a vendor-specific network. Standardized protocols are designed to make it possible to establish communication among computers developed by different vendors. This is an essential aspect of a general-purpose, open II.

Types of Standards

Standards abound. David and Greenstein (1990, 4) distinguish among three kinds of standards: reference, minimum quality, and compatibility standards. II standards belong to the last category: they ensure that one component may be successfully incorporated into a larger system because it adheres to the interface specification of the standard. One may also classify standards according to the processes by which they are established. A distinction is often made between formal, de facto, and de jure standards. Formal standards are worked out by standardization bodies. Both OSI and Internet are formal according to such a classification.[4] De facto standards emerge when technologies are standardized through market mechanisms, and de jure standards are imposed by law.

The compatibility standards related to II form a complex network. There are, for instance, 201 different Internet Standards.[5] These standards do not all fit into a tidy, monolithic form. Their interrelationships are highly complex. Most OSI and Internet standards are organized in a hierarchical fashion; others are partly overlapping (for instance, application-specific or regional standards may share some but not all features). Standards can also be replaced, wholly or only in part, by newer ones, creating a "genealogy of standards." The heterogeneity of II standards, the fact that one standard includes, encompasses, or is intertwined with a number of others, is an important aspect of II. It has, we argue, serious implications for how the tension between standardization and flexibility unfolds in II. The protocol for E-mail in the Internet can serve as an illustration.

E-mail is one of the oldest services provided by Internet. The current version of the standard for E-mail, which dates back to 1982, developed through revisions spanning three years. A separate standard specifying the format of the E-mail message was launched in 1982 together with the protocol itself. An earlier version of formats for E-mail goes back to 1977. This historic development was basically one of substitution in which one standard was being replaced by another, more or less equivalent one. However, the relationship between standards is not always so clear-cut. The conceptually self-contained function of providing an E-mail service becomes increasingly entangled with an array of previously unrelated issues. For example, the standard for E-mail is now being aligned with the rapidly growing body of previously unrelated standards for coding and representation of data types for video, audio, bit maps, graphics, and enriched alphabets (RFC 1994b). In the Internet community, a number of standards define how other standards should be interconnected (for instance, how one protocol should be used on top of or within another).

Within OSI, profiles are used to specify relationships among standards. An OSI "profile" is a defined selection among the many options offered by the standard. A profile specifies which options of a protocol are necessary for a given kind of use and, once an option is chosen in one protocol, which options are necessary in the underlying protocols. Governments in several countries are defining their national OSI profiles. Because the number of options is significant, the description of a profile is a voluminous document. As a consequence, two different national profiles are likely to be incompatible.

OSI and Internet: The Standards

Most of the OSI and Internet standards are organized in a hierarchy (that is, they are layered). Within this layered configuration of OSI and Internet, each layer is separately black-boxed: standards do not specify how a given layer must accomplish its tasks, only what it must accomplish.

OSI consists of two parts, a communication model defining seven layers of protocols and the specific protocols. There is one protocol for each layer except the seventh, which contains several protocols (in which we find services like E-mail, file transfer, and directory services). The seven layers of the OSI model are called the physical, link, network, transport, session, presentation, and application levels. The OSI model defines a protocol as the "language" used by two computer systems. The implementation of a protocol is called a protocol element. A protocol element provides services to the components that want to communicate using this protocol element. It is implemented on the basis of lower-level protocols' services.

Internet is in principle organized in the same manner, but it is much simpler. It has only three layers: Internet Protocol (IP; corresponding to the network layer of OSI), Transmission Control Protocol (TCP; corresponding to the transport layer), and the application layer (in which we find services like E-mail, News, ftp, gopher, WAIS, and World Wide Web; see Krol 1992).

OSI and Internet: The Standardization Process[6]

The development of OSI protocols follows (in formal terms) democratic procedures, with representative participation under the supervision of the ISO (Lehr 1992). Anyone can participate in the development process. Standards are approved according to voting procedures in which each country has a predefined number of votes. The national representatives are appointed by the national standardization bodies.

OSI protocols are developed by first reaching a consensus about a specification of the protocol. The protocol specifications are assumed to be implemented as software products by vendors, but implementation is independent of the standardization process. Because of the formal and political status of OSI protocols, most Western governments have decided that II in the public sector should be based on OSI protocols.

The implementation and diffusion of OSI protocols have not proceeded as anticipated by those involved in the standardization processes. The protocols have been developed by large groups of people who have been specifying them without being directly involved in implementation and without considering compatibility with non-OSI protocols (Rose 1992). This results in complex protocols and serious unforeseen problems. The protocols cannot run alongside other networks, only within closed OSI environments. They are big, complex, ambiguous, and difficult to implement in compatible ways by different vendors. The definition of profiles mentioned earlier is an attempt to deal with this problem.

The development process of Internet protocols follows a pattern different from that of OSI (RFC 1994a; Rose 1992). Internet is formally independent of ISO. It is open to anyone who is interested and does not attempt to ensure representative participation.[7] Standards develop through three phases that explicitly aim to interleave the development of the standard with its practical use and evaluation (RFC 1994a, 5). During the first phase (a Proposed Standard), known design problems should be resolved but no practical use is required. In the second phase (a Draft Standard), at least two independent implementations need to be developed and evaluated before the standard may pass on to the final phase—that is, to be certified as a full Internet Standard. This process is intended to provide opportunities for improvement of those features that are found wanting and to ensure that the protocols are lean, simple, and compatible with the already-installed base of networks.

The two approaches followed by OSI and Internet can be presented as two archetypical approaches to the development of II based on different underlying assumptions and beliefs. The principal underlying assumption of OSI's approach is that II standards should be developed in much the same way as it is done in traditional software engineering—namely, by first specifying the systems design, then implementing it in software products, and finally, putting it into use (Pressman 1992). Technical considerations dominate. Like traditional software engineering (Pressman 1992, 771), OSI relies on a simplistic, linear model of technological diffusion, and in this case, on the adoption of formal standards. The standardization of Internet protocols is based on different assumptions. The process is close to an approach to software development that is much less widely applied than the traditional software engineering approach explained above. This approach emphasizes prototyping, evolutionary development, learning, and user involvement (Schuler and Namioka 1993). In the Internet approach, the standardization process unifies the development of formal standards and their establishment as de facto ones. The question of whether Internet's approach has reached its limits is currently the subject of an interesting and relevant discussion (see Eidnes 1994, 52; Steinberg 1995, 144) prompted by the fact that it is not the technology alone that is undergoing changes. As the number of users grow, the organization of the standardization work also changes (Kahn 1994).

Flexibility

Having outlined the content and organization of the OSI and Internet standardization processes, we now turn to the issue of flexibility. Standardization, we argue, is frequently interrupted and interleaved with events that require that the standards be flexible and that they be easy to change. We discuss what generates needs for change, how flexibility and change are made possible, and, perhaps most important, how they are hampered.

The Need for Change

The need for an II to change may be illustrated by a few of the changes of some OSI and Internet standards during their lifetimes.

OSI protocols have in general been quite stable after their formal approval. The OSI standard for E-mail, however, did change: the standard approved in 1984 was replaced by a new version four years later. The new version differed so much from the earlier one that a number of their features were incompatible (Rose 1992).

Internet has so far proved remarkably flexible, adaptable, and extendable. It has undergone substantial transformations, constantly changing, elaborating, or rejecting its constituting standards. To keep track of all the changes, a special report that is issued approximately quarterly gives all the latest updates (RFC 1995). These changes take place in a period of diffusion that itself necessitates changes. The number of hosts connected to Internet grew from about 1,000 to over 300,000 between 1985 and 1991 (Smarr and Catlett 1992). The Matrix Information and Directory Services estimated the number of hosts at about 10 million in July 1995 (McKinney 1995).

The need for an II to continue changing while it is diffusing is recognized by the designers themselves. An internal document describing the organization of the Internet standardization process states: "From its conception, the Internet has been, and is expected to remain, an evolving system whose participants regularly factor new requirements and technology into its design and implementation" (RFC 1994a, 6).[8]

The Internet Engineering Task Force has launched a series of working groups that, after four to five years, are still struggling with different aspects of these problems. Some of the problems result from the introduction of new requirements posed by new services or applications. Examples are asynchronous transmission mode, video and audio transmission, mobile computers, high-speed networks (ATM), and financial transactions (safe credit card purchases). Other problems—for instance, routing, addressing, and net topology—are intrinsically linked to and fuelled by the diffusion of the Internet (RFC 1995).

Nothing suggests that the pace of change or the need for flexibility of the Internet will decrease (Smarr and Catlett 1992; RFC 1994a, 1995).

Between 1974 and 1978, four versions of the bottom-most layer of the Internet—that is, the IP—were developed and tested (Kahn 1994). For almost fifteen years, IP has been practically stable. In many respects, IP is the core of the Internet because it provides the basic services that all other services build upon. An anticipated revision of IP is today the subject of "spirited discussions" (RFC 1995, 5). The stakes are high, and the problems with the present version of IP are acknowledged to be so grave that Internet, in its present form, will not be able to evolve for more than an estimated ten years without ceasing to be a globally interconnected network (RFC 1995, 6-7; Eidnes 1994, 46). Among the serious and still unresolved problems, one of the most pressing ones is the concern that the "address space" will run out in a few years. The Internet is based on the fact that all nodes (computers, terminals, and printers) are uniquely identified by their addresses. The size of this space is finite and determined by how one represents and assigns addresses. The problem with exhausting the current address space is serious because if it is not resolved, any further diffusion of Internet will be blocked for the simple reason that there will not be any free addresses to assign to new nodes wishing to hook up. The difficulty is that if one switches to a completely different way of addressing, one cannot communicate with the "old" Internet. One is accordingly forced to find solutions that allow the "old" (that is, the present) version of IP to function alongside the new and not yet existent IP.

Because the components of IIs are interconnected, standardization of one sometimes requires changes of other components. For example, enabling mobile computer network connections requires new features that must be added to IIs (Teraoka et al. 1994). These may be implemented as extensions to the protocols at the network, transport, or application level of the OSI model. If one wants to keep one layer stable, others must change.

Enabling Flexibility and Change

II consists of a highly complex and extensive physical network of interconnected modules of communication technology. The only feasible way to cope with such a network is by modularization—that is, by decomposition or black-boxing.

Most engineers, not only those involved with II, use modularization as a strategy for coping with design (Hård 1994). In the case of computer science (including the development of II), modularization is systematically supported through a large and expanding body of tools, computer language constructs, and design methodologies. Elaborating this would carry us well beyond the scope of this article, but the historical development of a core element of computer science—namely, the evolution of programming languages—has been greatly influenced by attempts to find constructs that could support long-term flexibility because they pragmatically restricted or disciplined local flexibility. One could thus recast the controversy over structured programming by recognizing the call for structured constructs as a means to allow for flexibility in the long run by sacrificing local flexibility of the kind the GOTO statement offers. (The GOTO statement offers great flexibility in how to link micro-level modules together at the cost of diminishing the possibilities of changing these modules later on.)

Decomposition and modularization are also the basis for flexibility in II: flexibility presupposes modularization. The effect of black-boxing is that only the interface (the outside) of the box matters. The inside does not matter and may accordingly be changed without disturbing the full system provided the interface looks the same. As long as a box is black, it is stable and hence standardized. In this sense, standardization is a precondition for flexibility.

Two forms of this modularization need to be distinguished. First, modularization may give rise to a layered or hierarchical system. The seven layers of OSI's communication model provide a splendid example of this. Each layer is uniquely determined through its three interfaces: the services it offers to the layer immediately above, the services it uses in the layer immediately below, and the services used by a sender and receiver pair on the same level.

Second, modularization may avoid coupling or overlap between modules by keeping them "lean." One way this modularization principle is applied is by defining mechanisms for adding new features without changing the existing ones. In the new version of IP, for instance, a new mechanism is introduced to make it easier to define new options (RFC 1995). Another example is the World Wide Web, which is currently both diffusing and changing very fast. This is possible, among other reasons, because it is based on a format defined in such a way that any implementation may simply skip or read as plain text those elements that it does not understand. In this way, new features can be added so that old and new implementations can run together.

Hampering Flexibility

Change of an II system is hampered when the two forms of modularization described above are not being maintained or when the diffusion of II impedes rapid implementation of innovations. An example of how the lack of hierarchical modularization may hamper flexibility can be found in OSI. In the application level standard for E-mail, the task of uniquely identifying a person is not kept separate from the conceptually different task of implementing the way a person is located. This hampers flexibility because if an organization changes the way its E-mail system locates a person (for instance, by changing its network provider), all the unique identifications of the persons belonging to the organization have to be changed as well.[9] Most OSI protocols are also good illustrations of violations of the "lean-ness" principle. Although the OSI model is an excellent example of hierarchical modularization, each OSI protocol is so packed with features that it is almost impossible to implement and even harder to change (Rose 1992). It is easier to change a small and simple component than a large and complex one. Internet protocols are much simpler—that is, leaner—than OSI protocols and, accordingly, are easier to change.

The third source of hampered flexibility is the diffusion of the II. As a standard is implemented and put into widespread use, the effort required to change it increases simply because changes need to be propagated to a growing population of geographically and organizationally dispersed users. This is captured by the notion of "network externalities" (Antonelli 1993; Callon 1994, 408) or the creation of lock-ins and self-reinforcing effects (Cowan 1992, 282-83).

Analysis and Discussion

Standardization of II has, of course, a lot in common with other sociotechnical processes of negotiation involved with appropriating any piece of technology. In this sense, standardization corresponds roughly to the process of closure, stabilization, and alignment (Bijker 1993; Callon 1991; Misa 1992). However, our description of II allows us to go beyond such rough correspondence between these concepts and to examine further the accumulation of resistance against change, the tight interconnection between different parts of an II including the entangled relationships among the standards and the dynamic and contingent alternation between stabilizing and changing a standard.

Concepts Applicable to II Development

The principle of interpretative flexibility (Law and Bijker 1992) stipulates that in principle, everything can be disputed, negotiated, or reinterpreted. Closure occurs when a consensus emerges—that is, when social groups involved in the designing and using of technology decide that problems arising during the development of a technology have been solved. Closure stabilizes the technology (Bijker, Hughes, and Pinch 1987; Bijker 1993). According to Misa (1992), closure has come to mean the process by which provisional facts or artifacts that are subject to a controversy are molded into a stable state characterized by consensus.[10] The actor network theory (ANT) addresses the additional question of how resistance against change may accumulate (Akrich 1992, 206). In his elaboration of ANT, Callon (1991, 1992, 1994) moves still closer to capturing the structuring abilities of artifacts. Standardization basically corresponds to aligning or normalizing an actor network. Callon's concept of the (possible) irreversibility of an aligned network captures the accumulated resistance against change quite nicely (Callon 1991, 1992, 1994). It describes how translations between actor networks are made durable and how they can resist assaults from competing translations. Callon (1991, 159) states that the degree of irreversibility depends on (1) the extent to which it is subsequently difficult to go back to a point at which that translation was only one amongst others and (2) the extent to which it shapes and determines subsequent translations.

The Irreversibility of II

Callon's (1991, 1992, 1994) notions of alignment and irreversibility capture a necessary aspect of standardization of II—namely, its growing resistance against change. Until now, the OSI protocols have not diffused very quickly. Several actors involved in the standardization of OSI and Internet (Rose 1992; Stefferud 1992) have suggested that the OSI failed because, in a phrase first coined by Stefferud (1992), it is "installed base hostile." In other words, the OSI protocols are not related closely enough to the already installed base of communication systems. The installed base is irreversible because the kind of radical, abrupt change implicitly assumed by the OSI developers is highly unlikely.

An actor network becomes irreversible when it is practically impossible to change it into another aligned one. Currently, Internet appears to be approaching a state of irreversibility. Consider the difficulties with the development of a new version of IP described earlier. One source of these difficulties is the size of the installed base of IP protocols that must be replaced while the network is running (cf. rate of diffusion discussed earlier). Another major difficulty stems from the fact that standards are interconnected. A large number of other technical components depend on IP. An internal report assesses the situation more precisely: "Many current IETF standards are affected by [the next version of] IP. At least 27 of the 51 full Internet Standards must be revised . . . along with at least 6 of the 20 Draft Standards and at least 25 of the 130 Proposed Standards" (RFC 1995, 38).

The irreversibility of II does not only have a technical basis. As II grows, it turns irreversible also because of the growing number of actors, organizations, and institutions involved and the increasing number of relations among them. In the case of Internet, this is perhaps most evident in relation to new commercial services promoted by organizations with different interests and backgrounds. The transition to the new version of IP will require coordinated action by all of these parties. There is a risk that "everybody" will wait for "the others," making it hard to be an early adopter.[11] As the number and variety of users grow, it becomes more difficult to reach agreement on changes (Steinberg 1995).

Beyond Irreversibility: Anticipated and Alternating Flexibility

The notions that at the present stage in our analysis pay most adequate justice to the accumulating resistance against change and the tight interconnection between different parts of an II are alignment, irreversibility, and, accordingly, momentum (Hughes and Callon both underline the similarities between these concepts; see Callon 1987, 101; Hughes 1994, 102). Despite their ability to account for the anticipated and interleaved flexibility of an II, these notions downplay this phenomenon to the point of disappearance. The problem becomes clear when we consider Hughes's (1994) discussion of momentum as a means for conceptualizing the development of infrastructure technologies.

Hughes describes momentum as a self-reinforcing process gaining force as the technical system grows "larger and more complex" (Hughes 1994, 108).[12] The rate of diffusion of Internet during recent years can serve as an indication of its considerable momentum. Major changes that seriously interfere with the momentum are, according to Hughes, only conceivable in extraordinary instances: "Only a historic event of large proportions could deflect or break the momentum [of the example he refers to], the Great Depression being a case in point" (Hughes 1994, 108) or, in a different example, the "oil crises" (Hughes 1994, 112).[13] This, however, is not the case with II. As the example of the next version of IP in Internet illustrates, radical changes are regularly required and even anticipated.[14] Momentum and irreversibility are accordingly contradictory aspects of II: if momentum results in actual—not only potential—irreversibility, then changes are impossible and II will collapse. Whether the proposed changes in Internet are adequate and manageable remains to be seen.

On the Scope of Our Analysis

Although we have tried to restrict our analysis to issues empirically present in II, our findings raise a number of more general issues. One way of discussing the scope of our analysis is to ask whether one needs to pay greater attention to differences between technologies. The STS insistence on the many forms of symmetries suggests that all types of technologies should be approached with the same methodological equipment. There seems to be no need for tailor-made analytical tools, only uniform ones. One of the principal strengths of STS is its attempt to tackle all kinds of technologies—bicycles, hamburgers, work practices, professional concepts, and hotel keys—with basically the same toolbox. Our analysis could be seen as challenging this.

First, our analysis of II provides a different entry to the debate over the scope and extent of interpretative flexibility (Winner 1993; Woolgar 1991). Instead of addressing this issue on a theoretical and general level, we work out an empirically based intermediate position that comes close to "soft" versions of technological determinism (Smith and Marx 1994). For example, it has been suggested that constructivist studies do not pay sufficient attention to the manner in which institutional arrangements hamper interpretative flexibility (Misa 1994). Our analysis shows that institutions play an important role in the development of large technical systems like II.

Second, our analysis suggests that we must aim to specify *relative degrees of flexibility*. Because the concern with maximizing flexibility in order to allow for future changes plays an important role in the standardization of II, one must constantly ask whether a specific solution A meets this requirement better than its alternative solution B—that is, whether the interpretative flexibility of A is greater than that of B.[15] To answer this question, it is clearly not sufficient to note that both A and B exhibit interpretative flexibility, that they both enable some actions while constraining others.

Third, our analysis of alternating and the anticipated flexibility of II suggests how important it is to be sensitive to the technology itself. Programmatically stating that standardization has a social and political content is rapidly becoming a cliché. Instead of repeating that both the standardization process itself and its effects are "intensely political" (Webster 1995, 30), we need to learn more about how the minute, technical issues—including data definition and coding—mesh with the nontechnical issues.[16]

Fourth, our study raises the question of to what degree the aspects of IIs we have identified are also present in other technologies. It seems reasonable to expect that the portrayed tension between standardization and flexibility in IIs would also be found in other "network technologies" such as telecommunications, railways, and power networks studied under the label "large technical systems." And our analysis extends still further if one is willing to go along with the kind of argument put forward by, for instance, Imai (1988) in which the complexity and interconnectivity of new technology is argued to be the main explanation for the establishment of what he calls the third generation of corporate networks in Japan in the seventies.

Notes

1. There is no unanimous abbreviation for information infrastructure. We follow the example of the Clinton/Gore plan, "National Information Infrastructure," which is usually abbreviated NII.

2. Internet started out as a research project in the late sixties aiming to establish a communication network between a number of institutions involved in research sponsored by the ARPA (Advanced Research Projects Agency).

3. Our strategy of comparing these two could be misinterpreted as assuming that their functionality, development, and history are similar. This is not our intention. By comparing them, we are promoting the more modest claim that they are similar enough to enhance our grasp of the dynamics of establishing an II.

4. This is the source of some controversy. Some prefer to regard OSI only as "formal" because of the properties of the standardization process described later. This disagreement is peripheral to our endeavor and is not pursued in this article.

5. In January 1995, there were 51 full Internet standards, 20 draft standards, and 130 proposed standards (RFC 1995, 38). An explanation of the difference between these categories of standards follows below.

6. Our study could be viewed as a basis for a comparative, institutional analysis of the development of II. Although beyond the scope of this article, an essential part of such an institutional analysis would be to discuss how the institutional arrangements also change in response to technological development (see Kahn 1994 for a brief outline of the evolution of the institutional arrangements of Internet). Graham et al. (1995) is a study that similarly could be viewed as an institutional-level analysis of technological development related to II. They discuss EDI by comparing the two institutions behind EDIFACT and ANSI X12. They remain, however, on the level of institutional analysis without, as we attempt, connecting this with the technology itself.

7. The term "Internet" may denote either (1) the set of standards that facilitates the technology, (2) the social and bureaucratic procedures that govern the process of developing the standards, or (3) the physical network itself (Krol 1992; RFC 1994a). This might create some confusion because a version of Internet in the first and third senses has existed for many years, whereas the second is still at work. We employ the term in the second sense in this context. The formal organization of Internet can be described in slightly more detail (RFC 1994a): anyone with access to Internet (that is, in the third sense) may participate in any of the task forces (called IETF) that are dynamically established and dismantled to address technical issues. IETF nominates candidates to both the Internet Advisory Board (IAB; responsible for the overall architecture) and the Internet Engineering Steering Group (IESG; responsible for the management and approval of the standards). The IAB and IESG issue all the official reports that bear the name "Requests for Comments" (RFC). This archive was established along with the conception of the Internet some twenty-five years ago. It contains close to 2,000 documents, including all the formal, proposed, draft, and experimental standards, together with a description of their intended use. The RFCs also record a substantial part of the technical controversies as played out within working groups established by the IETF or independent comments. Minutes from working group meetings are sometimes published as RFCs. In short, the RFCs constitute a rich archive that sheds light on the historic and present controversies surrounding the Internet. It seems to be a rather neglected source of information and, accordingly, an ideal subject matter for an informed STS project providing us with the social construction of Internet. It is an electronic archive that may be reached by World Wide Web using http://ds.internic.net.

8. A similar situation is described in Star and Ruhleder (1994) in which the perceived requirements from the various groups of users varied over time.

9. X.400, the E-mail standard of OSI and CCITT (the international body within the United Nations concerned with telecommunications), includes a so-called private domain in a person's address. This private domain will typically identify the organization providing the X.400 E-mail service. It accordingly mixes routing with addressing information.

10. One might be tempted to "test" closure, stabilization, and alignment more systematically against the three crucial aspects of II identified above. Our selective strategy does not accomplish this. Still, it seems to us that closure fails to account for the alternation between stability and change. The notion of degrees of stabilization is an improvement in this respect as it allows for this, but it does not conceptualize the phenomenon as such (Bijker 1993, 121-122), and it does not relate it to the tight interconnection between the components of an II.

11. Several authors have argued that the interconnectivity and lack of common authority require that IIs are win-win situations—that is, everyone stands to win with none to lose (Krcmar et al. 1993; Trauth, Derksen, and Mevissen 1993). This needs to be taken in a stronger sense than the notion of win-win normally suggests. Building strong scenarios, enrolling the actors

through translations, and establishing an obligatory passage point may include a dynamically negotiated structure of incentives as an integral part of the design process. In particular, this reinforces the argument by Kling (1987) that the boundary that defines the relevant groups cannot be defined a priori—not only, as Kling suggests, because the "impact" is difficult to assess beforehand but also because this boundary may be dynamically redefined as part of the process of developing an incentive structure (Monteiro, Hanseth, and Pedersen 1994).

12. This also counts as an objection against the simplicity of the notion of "critical mass" (Rogers 1989).

13. We are forced to resort to examples in our discussion of Hughes's notion of momentum because this is the only way he himself explains it (Hughes 1994, 102).

14. Hughes seems lately to have modified this (Hughes 1994).

15. A variant of this concerns the question of the usefulness of holding on to the notion of "phases" in technological development. Hughes (1987, 57) argues that instead of disposing of it like Bijker (1992), a "soft" version of it is useful as it enables us to talk of activities that "predominantly" take place in "phases."

16. Lobet-Maris and Kusters (1993, 140) face a similar problem when they end their inquiry by suggesting that EDIFACT is "open" (read: flexible) because it is not a proprietary standard without discussing how this flexibility is exercised. (EDIFACT stands for Electronic Data Interchange in Administration, Commerce and Transport and is a United Nation standard for defining EDI message.) Likewise, Trauth, Derksen, and Mevissen (1993) locate flexibility at a national or cultural level.

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