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Perspectives on infrastructure

My approach to infrastructure builds upon several different traditions, including but not limited to history and sociology of science and technology; historical economics; standardization process studies; and information science. With apologies for the many italicized terms, this section offers an extremely condensed overview of this large literature, highlighting concepts I will use throughout this book.

In a widely cited article, Star and Ruhleder noted the following major characteristics of infrastructure in general:

- Embeddedness. Infrastructure is sunk into, inside of, other structures, social arrangements, and technologies.
- Transparency to users.
- Learned as part of membership in a community of practice. Strangers and outsiders encounter infrastructure as a target object to be learned about. New participants acquire a naturalized familiarity with its objects as they become members.
- Embodiment of standards. Infrastructure takes on transparency by plugging into other infrastructures and tools in a standardized fashion.
- Built on an installed base. Infrastructure… wrestles with the inertia of the installed base and inherits strengths and limitations from that base.
- Becomes visible upon breakdown.
- Is fixed in modular increments, not all at once or globally. Because infrastructure is big, layered, and complex, and because it means different things locally, it is never changed from above. Changes take time and negotiation, and adjustment with other aspects of the systems involved (excerpted from Bowker and Star, 1999, 35; originally published in Star and Ruhleder, 1996).

The deep insight of this description regards the mutual co-constitution of infrastructure's technical, social, and experiential features. Infrastructures reside in a naturalized background, as ordinary and unremarkable to us as trees, daylight, and dirt. Our civilizations fundamentally depend on them, yet we notice them mainly when they fail, which they rarely do. They are the connective tissues and the circulatory systems of modernity. By linking macro, meso, and micro scales of time, space, and social organization, they form the stable foundation of modern social worlds. To be modern is to live within and by means of infrastructures, and therefore to inhabit, uneasily, the intersection of these multiple scales (Edwards, 2002).

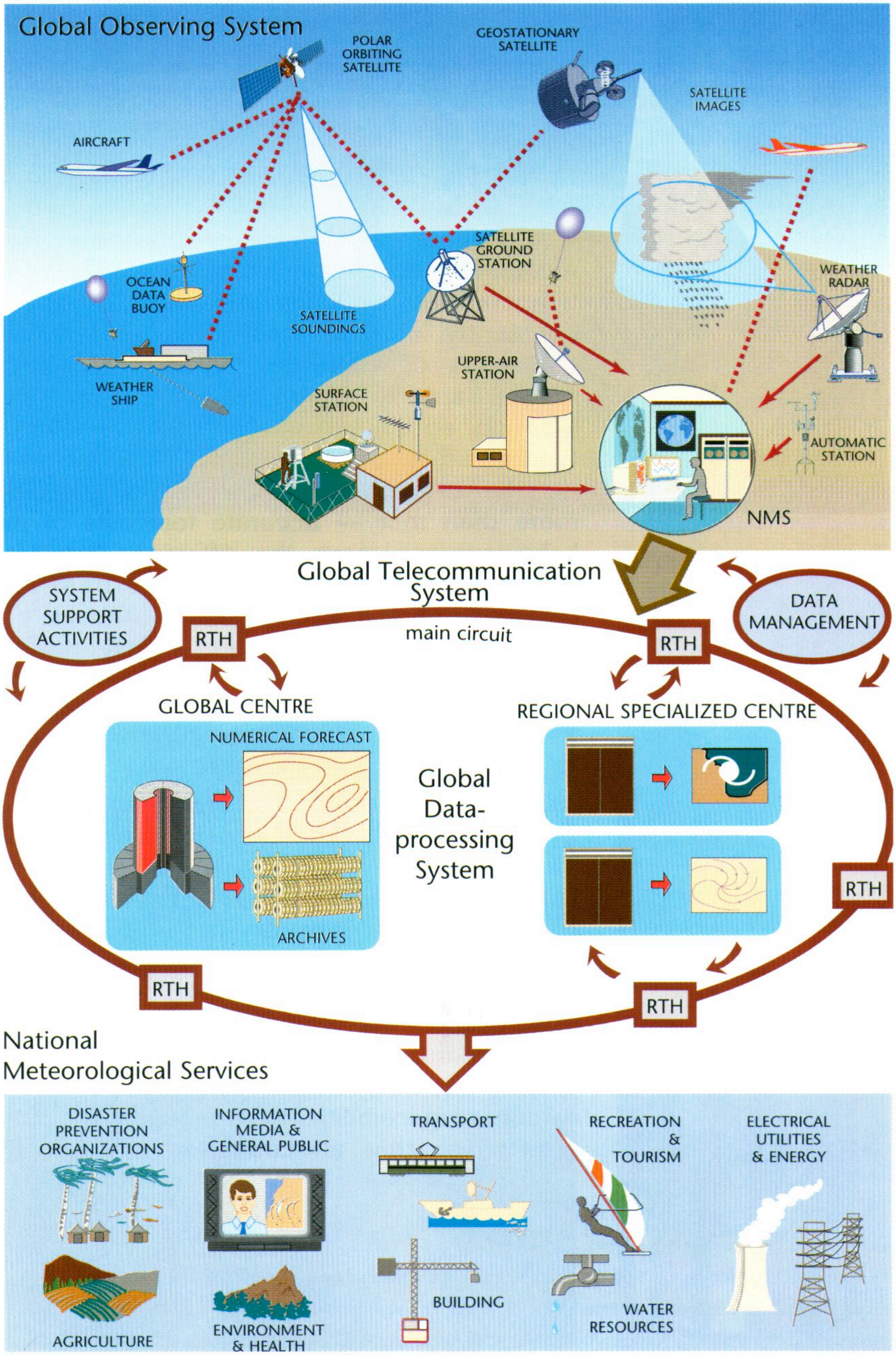
Infrastructural systems are by definition ubiquitous and widely shared, at least within a given nation or society. Many are transnational and a few, such as the telephone system, are effectively global. Most entities typically classified as "infrastructure," such as railroads, electric power grids, and telephone systems, are network technologies that channel flows (of goods, energy, information, money, etc.) between places and people. From this point of view, infrastructures fall into three basic categories:

- Accumulative: collect material, information, etc. at a central point for use or disposal. Examples include sewer systems; waterways used by loggers to move logs to downstream sawmills. The Global Observing System shown in Figure 1 is accumulative, collecting information from a vast sensor network for processing at central nodes.

- Distributive: send material, information, etc. from a central point to widely distributed nodes. Examples include water supplies, electric power, and broadcast media such as radio and television. The Global Data Processing System shown in Figure 1 consists of a few central nodes that distribute weather and climate information to National Meteorological Centers, which in turn distribute weather information to mass media, agricultural stations, and so on.

- Communicative: flows move in both directions, as in the Global Telecommunication System of Figure 1. Communicative infrastructures are often true networks, connecting many individual nodes in a non-hierarchical system that lacks a central leverage point [get cite from Arne].

Increasingly, information technology-based communicative elements are being added to accumulative and distributive infrastructure networks, permitting fine-grained feedback for control and service improvement.


Global Observing System
POLAR ORBITING SATELLITE
GEOSTATIONARY SATELLITE
SATELLITE IMAGES
AIRCRAFT
SATELLITE GROUND STATION
WEATHER RADAR
OCEAN DATA BUOY
SATELLITE SOUNDINGS
UPPER-AIR STATION
WEATHER SHIP
SURFACE STATION
AUTOMATIC STATION
NMS
Global Telecommunication System
SYSTEM SUPPORT ACTIVITIES
DATA MANAGEMENT
main circuit
RTH
RTH
GLOBAL CENTRE
REGIONAL SPECIALIZED CENTRE
NUMERICAL FORECAST
Global Data-processing System
ARCHIVES
RTH
RTH
RTH
National Meteorological Services
DISASTER PREVENTION ORGANIZATIONS
INFORMATION MEDIA & GENERAL PUBLIC
TRANSPORT
RECREATION & TOURISM
ELECTRICAL UTILITIES & ENERGY
BUILDING
WATER RESOURCES
AGRICULTURE
ENVIRONMENT & HEALTH

Network technologies share a number of crucial features. First, they exhibit what economists call network effects: exponentially increasing benefits from widespread adoption. Second, they often appear to be natural monopolies, at least initially; natural monopolies benefit from economies of scale to the point that maximum efficiency is achieved through a single supplier. Conditions favoring natural monopoly can change, for example when new information technology and/or organizational techniques permit the unbundling of a set of services into separate streams supplied by different, potentially competing entities (Graham and Marvin, 2001).

Figure 1. The contemporary global meteorological data network (Korea Meteorological Administration, unknown). In the diagram, RTH stands for "regional telecommunications hub."

Many (not all) infrastructures are public goods. In economic terms this means they are non-rivalrous, i.e. one individual's consumption or use of the good does not leave less of the good for others (examples are broadcast television and the Internet). Often, but not always, public goods are non-excludable as well. This means that it is difficult or undesirable for technical, social, and/or political reasons to substantially restrict access to them, or to charge for such services on the basis of actual use. In the developed world, sewer systems and water supplies are good examples of non-excludable infrastructures. It is technically feasible to exclude people from using sewers and purified water supplies, but doing so is socially and politically undesirable. Hence many municipal governments undertake to provide such services directly and to promote or even require their use. (This example also shows how local and national conditions can affect the status of a good; in the developing world, sewer systems and purified water supplies may be available only to elites.) On a national scale, telephone networks have acquired public good characteristics as they became indispensable (for example, in accessing emergency services). Regulatory policies providing for "universal" access and telecommunications monopolies administered by national governments became commonplace as a result (Graham and Marvin, 2001).

While there is no such thing as a general theory of infrastructure, historical development patterns share striking similarities across diverse technologies and organizational forms. These patterns were first identified by a loose-knit collection of American and European historians known as the Large Technical Systems (LTS) group, which produced a number of monographs and edited collections usually traced to Thomas Parke Hughes' landmark study Networks of Power. That book compared electric power development in the US and several European countries (Hughes, 1983).

Hughes discerned a series of developmental stages that appeared to hold across many cases. These are:

- Invention
- Development
- Innovation
- Technology transfer
- Growth
- Competition
- Consolidation

First a new technology is invented. Development and innovation phases follow. During these three stages, system builders create and promote linked sets of devices that fill a functional need. Hughes's paradigmatic example of a system builder is Thomas Edison, whose generator-cable-light bulb system fulfilled needs for lighting; the point is that the lighting system was the ground for Edison's commercial success, rather than the more famous light bulb (simultaneously developed by several other inventors) or the provision of electricity per se. Further, technical achievements alone are never sufficient. Where it succeeds, system building always includes organizational, financial, and marketing efforts. Other historians have noted the common phenomenon of system-builder teams made up of one or more technical "wizards" or "supertechs," who handle system conception and innovation, working together with a "maestro," who orchestrates the organizational, financial, and marketing aspects of the new system. Such teams may also include a charismatic "leader" who stimulates external interest in the project, promoting it against competing systems and generating widespread adoption (McKenney et al., 1995). These terms label roles, not people; they may be held by individuals or groups, as well as in various combinations.[1] As it develops, a new LTS requires not only further technical innovation but also further organizational, economic, political, and legal activity in order to a host of heterogeneous problems. Here the "leader" role becomes particularly important, while the system begins to incorporate numerous heterogeneous components; finance capital, legal representation, and political and regulatory relationship management become indispensable elements of the total system. By this point the LTS has become fully sociotechnical, rather than merely technological.

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[1] Well-known examples of such teams are: in telephony, Alexander Graham Bell (wizard) and Theodore Vail (maestro/leader, AT&T; Friedlander, 1995b); Tim Berners-Lee (wizard) and Robert Caillau (wizard/maestro, the World Wide Web; Berners-Lee and Fischetti, 1999); and James Bryce (wizard) and Thomas Watson Sr. (maestro/leader, IBM; Pugh, 1995).

Once an LTS has been succesfully constructed in one location, technology transfer to other locations (cities or nations) often follows. Typically, variations in the original system design and organization are introduced in response to differences in local conditions (Coutard et al., 2004). This adaptation leads to a phenomenon Hughes called “technological style,” which describes the distinctive look and feel of the “same” technical system as it appears in differing local and national contexts.

During the subsequent growth phase, competing systems may be introduced with dissimilar, frequently incompatible properties. In the early days of electric power, for example, competition occurred among systems with differing standards for line voltage. Both direct and alternating current systems developed, each with its own advantages. In the quasi-final stage of LTS development, consolidation, competition among technological systems and standards is resolved either by the total victory of one over the others (the rare case), or (more often) by the appearance of gateway technologies which allow previously incompatible systems to interoperate. The rotary converter, for example, allowed AC power to be converted to DC on a large scale, permitting competing electrical distribution systems to be connected (David and Bunn, 1988). AC/DC power converters for consumer electronics and telephone adapters for international travel are mundane examples. Gateway technologies may be conceptualized more simply as plug-and-socket systems. By allowing heterogeneous technical systems to interoperate, gateway technologies and standards permit the creation of networks such as power grids, railroad, and telephone networks.

Tineke Egyedi has argued that gateway technologies confer differing degrees of flexibility on technical systems depending on the degree to which they are standardized (Egyedi). Gateways may be dedicated (improvised, or fit specifically to a particular system); generic (standardized sockets opening one system to interconnection with others); or meta-generic (“modeled,” i.e. specifying a framework or protocol for the creation of specific generic standards, without specifying those standards directly). Table 1 outlines Egyedi’s framework.

Degree of Standardization	Scope of Gateway Solution	Examples
High (modelled)	Meta-generic	OSI[2]
Medium (standardized)	Generic	XML, Java, ISO container[3]
Low ('improvised')	Dedicated	AC/DC rotary converter

Table 1. Relationship between degree of standardization and scope of gateway solution (from Egyedi)

Gateway technologies of all three types are common in the world of information technology (IT), where software patches allow one document format to be converted into another; one operating system to emulate the properties of another; and so on, but they can occur in other systems as well.

The growth and consolidation phases of Hughes's model mark a key transition from homogeneous, centrally controlled, often geographically local systems to heterogeneous, widely distributed networks in which central control may be partially replaced by coordination processes. It is typically only in the consolidation phase, with the appearance of standardized, generic gateways, that most LTSs become <u>infrastructures</u> on a national, and especially on a transnational scale. For example, in the mid-19th century national telegraph systems were rapidly interconnected; one of the first intergovernmenal organizations, the International Telegraph Union (ITU), arose to create standards that functioned as gateway technologies connecting these systems into a transnational and eventually global infrastructure. Most national systems were centrally controlled; standards and other gateway technologies permitted coordination of the international network without central control. Thus not all LTSs become infrastructures. Conversely, not all infrastructures fit the LTS model, since some entitites readily classifiable as infrastructures (such as schools, prisons, and legal systems) did not originate as inventions (in the narrow sense), and rely less heavily on a specifically technological base.

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[2] The Open Systems Interconnection Reference Model defines seven "layers" of computer network function, from physical links to applications. Within each layer, standards can evolve separately so long as they conform to the model (see Abbate, 1999, Chapter 5).

[3] XML is the eXtensible Markup Language. Java is a cross-platform computer language. ISO (International Standards Organization) container refers to standard sizes, shapes, and connectors for shipping containers used for freight transport by ship, rail, and truck.

Further, the stages of the Hughes model do not necessarily occur in lockstep sequence. Overlapping and backtracking are in fact common in historical LTS development. However, once consolidation into a network has occurred, LTSs typically acquire what Hughes called technological momentum, a metaphor borrowed from physics that indicates the increasing difficulty of altering the LTS's form and function. Spelling out the metaphor further, momentum has three components: mass (large size and extent of both technical and organizational components), velocity (rate of growth), and direction (system goals and functions). Like most recent historians and sociologists of technology, Hughes stressed that technological momentum was not equivalent to technological autonomy. Instead, the metaphor was an indication of the increasing difficulty of changing any large system as vested interests, sunk costs, and fixed assets grew in scale and scope. Historical economists have named this phenomenon path dependence, pointing the increasing mass not only of tangible assets but also of human skills and the related training systems.

Other, complementary studies of infrastructure have stressed that governments often play a key role, first in support of development during the innovation, transfer, and growth phases, and later as regulators during and after the consolidation phase (Friedlander, 1995a; Friedlander, 1995b; Friedlander, 1996a; Friedlander, 1996b). In many cases governments are also the owners and operators of LTSs, as in the case of municipal water supplies and national Post, Telephone, and Telegraph (PTT) services. Recently, historians have begun attending to the role of infrastructure in transnational linking and delinking as well. Transborder bridges and tunnels; links between national telegraph and telephone systems; containerized international shipping and road/rail transport; airports; and many other infrastructure projects involve resolution of political, legal, and financial issues simultaneously with technical standards. Delinking also occurs, particularly in wartime, when transnational infrastructural links are usually among the first objects of military engagement (Schot et al., 2006).

The basic outlines of Hughes's model have been well confirmed across numerous LTSs. The Large Technical Systems group established an "LTS approach" or "sociotechnical systems research methodology" that was widely adopted, most notably in Europe by Dutch, Swedish, German, and French scholars (Blomkvisk and Kaijse, 1998, #51581; Bijker et al., 1987; Mayntz and Hughes, 1988; La Porte, 1991; Bijker and Law, 1992; Braun and Joerges, 1994; Kaijser, 1994; Summerton, 1994; Gras, 1997; Hughes, 1998; Coutard, 1999; Coutard et al., 2004; Hughes, 2004). The diversity of languages and journals has limited the dissemination of some of the most important LTS work in the English-speaking world. In a perceptive recent review, Erik van der Vleuten notes several key features of this approach. First, he points out, "the notion of 'large technical systems' has a double meaning: it refers to a category of phenomena as well as a research methodology. Indeed, some authors do not distinguish between research object and method, … [and] there is no consensus on a strict definition of the research object LTS." Van der Vleuten notes the resemblance of the research object LTS to infrastructure, but demonstrates that writers in the LTS field vary dramatically in their conception of relations between the social and the technical:

> some authors define LTSs as sociotechnical entities and reject any distinction between 'the technical' and 'the social', while for others LTS rather are society-wide 'technologies.' Some presuppose central system builder control over all system elements (and exclude more anarchistic systems such as road and water transport), while others make a point of studying self-regulation or 'loosely-coupled systems'. Some define LTS by function (communication, transport, energy supply) while others investigate their multifunctionality (van der Vleuten, 2004, 400).

Core features of 'the' LTS research methodology, van der Vleuten writes, include the following:

- The construction of LTSs is analyzed from the perspective of privileged actors ('system builders') who manipulate and juxtapose 'heterogeneous' elements, ranging from artefacts to organization structures, licensing strategies, and advertising…;
- 'The' LTS approach… also uncovers how the agendas of system builders become inscribed in the technical features of infrastructural technologies…;
- A 'follow the actor' [analytical] strategy… accounts for system changes by dissolving the actor-structure cleavage (van der Vleuten, 2004, 399-400, reorganized).

At first the LTS approach was mainly applied on the basis of underlying technology, rather than across LTSs based on their function. For example, studies compared telephone systems in different national contexts, rather than studying point-to-point communication as a functional whole. The LTS approach was also criticized for focusing on engineers and other privileged actors to the exclusion of, for example, technically innovative users.

However, more recent work has recognized these challenges, identifying integration across technical systems as a crucial aspect of infrastructure. In 1994 the German sociologist Ingo Braun introduced the influential concept of "second-order large technical systems." Rather than introduce entirely new, separately constructed technical frameworks, second-order

LTSs serve new functions or uses by combining capabilities of existing, first-order LTSs. His own principal example is the European organ transplant network, which joins hospitals, transport systems, and information technology to create a system for rapid matching of donor organs with patients. Braun's phrase for this second-order LTS creation, Vernetzung der Netze, has been translated as "material interlacing," but a more literal rendering would be "networking of networks."

The example also illustrates how users of first-order LTSs can become LTS system builders in their own right, bypassing the invention phase because they what they are building relies on existing infrastructure. This relates to another crucial concept in LTS historiography, often called the "user heuristic" (after Fischer, 1992). The user heuristic reminds historians of technology to focus on how end users of any technology, including LTSs, tend to produce new uses and system configurations unforeseen by the system builders on whom Hughes's model relies so heavily. User innovation can alter the direction (goals) of an LTS, affecting its "technological momentum." Well-known examples of user innovation include using the telegraph and telephone for sociability purposes (as opposed to business; Fischer, 1988); use of the early ARPANET for email and newsgroups (Hafner and Lyon, 1996; Abbate, 1999); and user conversion of early automobiles into trucks that competed unexpectedly with rail for medium-haul transportation early in the 20th century (Goddard, 1994).

When users kluge together a network or internetwork in order to achieve a functional goal, innovators may find it possible to create gateway technologies that link heterogeneous systems. This was the case, for example, with both the Internet (which linked heterogeneous networks by means of the protocol known as TCP/IP), and the World Wide Web, which began as a protocol for the exchange of hypertext documents but rapidly subsumed numerous pre-existing Internet functions, such as ftp, gopher, and news, within the technology of the Web browser. The dynamic may be summarized as follows: systems work well because of their limited scope and centralized control. Systems gain scale by being connected with other compatible systems. Users appreciate increased scale, but they also want increased scope; for this purpose they tend to employ multiple systems and networks, generating internetworks, webs, or second-order LTSs. Gateway innovations and shared standards can sometimes make networks and internetworks behave more like systems, increasing transparency and functionality. This benefits users. However, gateway innovations can have unpredictable effects on the owners and operators of underlying systems; hence they are not always embraced.[4] Even in IT, where it is often easier than in other domains, the standardization process is hardly a smooth road:

> Information technology standards have been touted as a means to interoperabiltiy andsoftware portability, but they are more easily lauded than built or followed. Users say they want low-cost, easily maintained, plug-and-play, interoperable systems, yet each user community has sepecific needs and few of them want to discard their existing systems. Every vendor wants to sell its own architecture and turbo-charged features, and each architecture assumes different views of a particular domain (e.g., business forms, images, databases). International standards founder on variations in culture and assumptions — for example, whether telephone companies are monopolies — in North America, Europe, and Asia (Libicki, 1995, 35).

No system or network will ever fulfill all possible user requirements. Therefore, new systems are continually invented and added to the existing stock, increasing complexity and adding to the difficulty of building seamless networks and internetworks.

The situation can thus be best described as a constant struggle between the desire for system-like behavior and the necessity of integration into higher-order networks and webs. The upshot is that where system builders seek well-defined market niches that can be served by the centrally designed and controlled systems, user goals revolve instead around functions that may be best served by linking the capabilities of separate systems. As LTSs enter the growth and consolidation phases, network effects tend to elevate the potential for user innovation from recalibration of system goals to genuinely transformative effects, while the possibility of building second-order LTSs from pre-existing infrastructural elements allows users to create new infrastructures without necessarily engaging in major engineering efforts.

In 1998, in an exploratory essay on the history of digital convergence, I argued that this pattern might be described as a trajectory from systems to networks to internetworks (or webs). Originally used to name the

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[4] This phenomenon can be readily re-described in the terms of actor-network theory (ANT, which is in fact best described as an ontology rather than a theory). Actors seek to increase their power by building alliances; such alliances can include technical as well as social links. Gateway technologies and standards fit this description well. ANT emphasizes that the effects of network extension are unpredictable (Callon and Latour, 1981; Callon, 1986; Callon, 1987; Latour, 1987; Law, 1987; Latour, 2004; Latour, 2005). Although ANT clearly fits the situation I am discussing in this book, its terminology and utility are obscure, and I do not pursue it further.

linking of heterogeneous computer networks (as in “the Internet”), the concept can be far more broadly applied. This is easy to see in the case of contemporary “digital convergence,” where previously separate information and communication networks such as cable television, radio, libraries, and telephony are merging in various configurations, both using and as digitization and the Internet bring a common technical base form to once-separate media. Table 2 summarizes this framework.

	Systems	**Networks** **(First-order Large Technical Systems)**	**Internetworks or Webs** **(Second-order LTSs)**
Key actors	System builders Users (adjustment roles)	Gateway builders Standards bodies Corporations & governments Users (transformative roles)	Gateway builders Standards bodies Corporations & governments Users (foundational roles)
Elements	Heterogeneous components and subsystems Dedicated gateways and standards	Heterogeneous systems Generic gateways (sockets, adapters) and standards	Heterogeneous networks Meta-generic gateways and standards
Control vs. coordination	Control Central, strong	Control and coordination Partially distributed, moderate strength	Coordination Widely distributed, weak
Boundaries	Closed, stable	Open, with standard sockets for new interconnections	Open, highly reconfigurable

Table 2. Information systems, networks, and internetworks (modified from Edwards, 1998).

The systems-networks-internetworks framework may be understood in two ways. First, on a synchronic axis, it identifies the nesting of systems within networks, which may in turn be nested within internetworks or second-order LTSs. Second, on a diachronic axis, it represents a development trajectory. As in the Hughes framework, however, movement along this path can go in both directions because, as observed above, system-builder goals tend toward centralized control (leading to re-integrated systems), while users seek functionality across systems (leading toward networks and webs).

Building on this scheme, Greg Downey analyzed what he calls

> the analog information internetwork, a century-old combination of character-transmission telegraph, voice-transmission telephone, and physical-transport Post Office networks. I call this an "analog" internetwork because… information could only move over each component network in a single form, requiring repeated physical translations as it moved through the internetwork (handwriting to voice to dot-and-dash and back again). Although the telegraph itself was in some sense 'digital'—based as it was on three possible states: no pulse, a short pulse (dot), and a longer pulse (dash)—those states were conveyed at varying cadences through the physical actions of rapidly pressing telegraph keys and attentively listening to telegraph sounders, and so were still analog at the core. … Historical actors who used and studied the telegraph, telephone, and Post Office saw the three as an internetwork. Business texts from the 1910s through the 1930s instructed students that proper business practice when sending telegrams involved all three media: even when paying for the 'report delivery' and 'repeat back' options to make sure telegrams were accurately transmitted and received (with those reports coming by telephone), important telegrams were to be 'confirmed immediately by a properly dated and signed letter' (Downey, 213-214).

Downey's argument shows that the systems-networks-webs dynamic can be extended beyond digital informatics to other modes of communication. Similar things may be said at least about transport internetworks linked through the agency of the ISO container (rail, shipping, trucking), and no doubt about many other infrastructural systems as well.

As we will see, the historical development of the weather and climate information infrastructure exhibits many features of this well-established pattern. The system-building phase begain with national meteorological services in the latter half of the 19th century. Each established its own system of data collection and forecast dissemination, based chiefly on telegraphy and postal mail. By the 1870s the need for gateway technologies to connect national systems had become acute. The International Meteorological Organization (IMO) was founded to negotiate standards and technical connections as the national weather services formed a loose network. With the proliferation of new intruments as well as new communications media (radio, microwave, telex, etc.), maintaining coordination in the international weather data network became ever more complicated in the first half of the 20th century. As both system builders and network users, the national weather services experienced sometimes conflicting pressures to improve national service while coordinating with other national services. After World War II, the IMO became the World Meteorological Organization (WMO), part of the new UN system of intergovernmental organizations. From the early 1960s, the balance in the WMO leaned in the direction of system-building, leading eventually to the World Weather Watch and other relatively unified global systems. Technical factors such as the emergence of satellites, far more amenable to centralized control than the distributed network of ground observing stations, helped in the construction of a more coherent and centralized system, but the overall structure remains even today a network based in the national weather services.

Information infrastructures and climate data

All true infrastructures are complex, but information infrastructures are arguably both the most complex and the most ubiquitous of all. Information is a dimension not only of the operation of all other infrastructures, but of human social life in general. Yet the technical complexity of semi-automatic information handling has proven so overwhelming that designers often ignore the social, organizational, and political dimensions of information creation, processing, and use. While the sophistication of information technology has increased at an awesome rate in the past half century, the sophistication of social information processing has not kept pace. For example, the notion of "information infrastructure" came into vogue in the mid-1990s with the rise of the Internet and World Wide Web, with which the phrase was often (incorrectly) identified. Few analysts differentiated the Internet as a communication system from the accumulative and distributive functions described above. Issues of long-term maintenance of scientific data, or of the proliferation of incompatible data storage systems, were rarely addressed in the rush to consider implications of the Web for commerce, copyright, and privacy.

This failure can be attribued in part to the fact that long-term data storage and maintenance depend as much on institutional structures and commitments as they do on technical capabilities. As John Seely Brown and Paul Duguid argue in The Social Life of Information,

> the communities, organizations, and institutions that frame human activities…, though vital to how we all live and work, are too often missing from the design stylebooks of the information age. Attending too closely to information overlooks the social context that helps people understand what that information might mean and why it matters (Brown and Duguid, 2000, 5).

The social and organizational context of technical information systems helps explain not only why computerization is rarely as easy or effective as its promoters expect (Landauer, 1995), but also why information itself often does not travel well (Collins, 1985; Collins and Pinch, 1993). Separated from its communal background of uses, habits, and skills, seemingly specific information can rapidly become ambiguous, meaningless, or irrelevant. The lens of infrastructural inversion helps us see other contextual dimensions of technical information systems as well. For example, new technologies enter an environment of preexisting systems and standards to which users are already committed. Interfaces must dovetail with human cognitive capacities, such as limited short-term memory and associative rather than hierarchical conceptual organization. The nature, quality, and technical means of communication in communities and organizations all influence how people learn to find and interpret information (Zuboff, 1988; Vaughan, 1996; Argote, 1999; Carroll, 2003).

Awareness of these issues stems from work in several streams of information science. The tradition known as "social informatics"[5] dates to the early 1970s, when Rob Kling and others introduced the concept of a "web of computing": the combination of social, organizational, and technological aspects that is always present in information systems, and which always governs the outcomes of changes (such as computerization) in how organizations handle data (Kling and Scacchi, 1982; Kling, 1999). Another, more recently established approach is the study of computer-supported cooperative work (CSCW), i.e. the use of information systems to aid group activity; academic CSCW scholarship has typically focused on small-scale, local collaborations (as in offices or corporations). The term CSCW dates to the early 1980s (Grudin, 1994), but as a phenomenon CSCW is much older, especially in those sciences which adopted computers as a fundamental tool as early as the 1940s. Meteorology — among the first sciences to employ computers — developed early and important applications of what would now be called CSCW techniques. As we will see, computerization's ripple effects soon reached almost every element of weather science. For example, it required all data to be converted to machine-readable formats, and it brought computer programmers into prominent positions in meteorological laboratories.

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[5] The useful word "informatics," coined in France in 1962, originally referred to the "science of rational treatment (notably by automatic machines) of information considered as support for human knowledge and communications in technical, economic, and social domains" (Académie Française, 1967, my translation). This early definition already captured the social dimension of information processing and the basic idea of computer-supported cooperative work. Edwards forthcoming (pompidou)

Archivists — professionally responsible for the long-term preservation of important records — have produced another, related stream of ideas in information science. Archives are formal collections of documents and records. They can accurately be called the infrastructure of historiography (the practice of writing history), since historians build their reconstructions of the past primarily from written records. As recent scholarship in archives and records management has shown, collections of historical materials are invariably shaped by selection and classification principles, which may be explicit or implicit, beginning with those of the original producers and extending down a chain of custody until they reach the hands of archivists themselves (, 1999). Archivists do their best, of course, to classify materials in ways that make them easy to search and retain what is known about their origins ("provenance"). Yet it is impossible, in the present, to know for certain exactly what people in the future will want to know about the past. Not infrequently, this means that information desired by historians is missing from documentary records. Furthermore, technical and economic considerations may limit the possible size of collections, and political or legal concerns can lead to the destruction of important documents (Hamilton; Foote, 1990). Yet the historian's ability to understand the significance of individual records often depends on knowing the context in which they were recorded, for example by whom, for what purpose, and to what effect. Archival collecting techniques — for example, the once-standard practice of cataloguing records in order of receipt, rather than by content or producer — can unwittingly fail to preserve the contexts that make records meaningful (Thomassen, 1971).

These concerns are, if anything, even more significant for scientific data than for documents and other kinds of records. Bowker's studies of attempts to build global biodiversity databases, for example, reveal issues all too familiar to archivists. A principal purpose of global biodiversity databases is to learn, in an era of mass extinctions, exactly which species are being lost. Since most species are known only through a single specimen, and many have very recently become extinct, scientific records from the past contain a great deal of information that may be irrecoverable (Bowker, 2000, 671). Yet data from the past is frequently rejected in modern biodiversity studies because it lacks crucial metadata. Metadata is information about data, for example where a specimen was collected, how it was preserved, how its characteristics were measured, etc. If information like this was not recorded by the originators and the original specimen itself was not preserved, it can be difficult or impossible to know exactly what the observer saw. This temporal dimension of what Bowker calls "datadiversity" has a complementary spatial dimension. Multiple, competing biodiversity projects based in different disciplines use fundamentally incompatible methods and norms, known to participants as “ecological” vs. “systematic biological” approaches (Bowker, 2000, 672).

Ole Hanseth and Eric Monteiro’s work on information infrastructures reinforces Bowker, Star, and Ruhleder’s analysis. They view information infrastructures as heterogeneous socio-technical networks which operate as “irreducible unit[s] shared by a larger community,” and which typically remain open to extension and linkage to other infrastructures (Hanseth and Monteiro, 1998). Studies of information infrastructures reveal how difficult the work of linkage can be in practice. Conflicts occur not only in the negotiation of standards, but in their implementation as well. Multiple standards cannot always be reconciled, and the phenomenon of parallel or overlapping information systems even within a single organization remains ubiquitous (Hanseth et al., 2006).

Bonnie Nardi and Vicki O’Day developed a similar analysis using the metaphor of “information ecologies.” The phrase describes local arrangements for storing and accessing knowledge, for example in libraries. The ecological metaphor captures several key features of local information systems. The latter consist of diverse, heterogeneous entities, including computers, software, books, librarians, and researchers. Like natural ecologies, they evolve in time. When one component changes, the others must respond: “people’s activities and tools adjust and are adjusted in relation to each other, always attempting and never quite achieving a perfect fit” (Nardi and O'Day, 1999, ??). Of interest here is the <u>fundamentally local</u> character of the information ecologies Nardi and O’Day describe, because it raises the question of <u>scale</u> — a crucial issue to which I will return throughout this book.

Anyone familiar with these literatures is forced to wonder how any information system organized around a universal standard of classification could ever function on a global scale. Indeed, Bowker believes that such systems do not now and probably cannot ever exist in science:

> The political possibility of an international consensus on the definition of biodiversity and the organization of a unified data-collection effort is slight…. Even if it succeeds, there will still be coding cultures specific to given locations and particular disciplines. … It may be theoretically possible to produce political agreements that would create a single integrated [biodiversity] database, but <u>no field at all has been able to make those agreements</u> — the field of medicine, for example, has been attempting to produce universal classifications for over a hundred years without success (Bowker, 2000, 676, emphasis added).

Rather than seek to build global panoptica incorporating universal classification schemes, he argues, we should look instead toward "oligopticons," or "machines that produce local orderings and alignments of datasets." Many other scholars have reached similar conclusions about the difficulties of producing global order (Jasanoff and Martello, 2004; Ong and Collier, 2005).

This is not just a matter of classification. It regards storing and maintaining data, not only in the straightforward sense of simply keeping all of the records and making them accessilble, but also in the far more complicated sense of maintaining social trust in the data's quality and legitimacy. Bowker notes that in the model inherited from experimental sciences, data are generated primarily to test theory. But this does not apply to field sciences like biodiversity, geology — or climatology. The statement that climate <u>change</u> is occurring is inherently comparative; it implies that we know what the climate used to be. We can know this only through data.

Thus the problems of social context, archival practice, local information ecologies, metadata, and scale arise directly in climatology, which (like geology, paleontology, or biodiversity studies) is an essentially historical science. Over the last century and a half, meterology and climatology gradually transformed themselves from local/regional to global sciences. This transformation changed the kinds of questions climate scientists asked, demanding not only new kinds of data but also new levels of data quality, accuracy, and consistency. Climate scientists seeking a highly accurate data image of past global climate cannot use meteorological records without key metadata for any particular data source. For example, when did new equipment replace older models at a given station? Did the station ever change location? (Moving even 100 meters can change readings significantly if, for example, the move was from the south to the north side of a hill.) When, by whom, and how well were station attendants trained in reading instruments and recording their results? How consistent were this station's records with others nearby? What might account for inconsistencies?

Answers to such questions are often unavailable or incomplete, especially for older data. As a recent review put it,

> for long-term climate analyses — particularly climate change analyses — to be accurate, the climate data used must be homogeneous. A homogeneous climate time series is defined as one where variations <u>are caused only by variations in weather and climate</u>. Unfortunately, most long-term climatological time series have been affected by a number of non-climatic factors that make these data unrepresentative of the actual climate variation occurring over time. These factors include changes in:

> instruments, observing practices, station locations, formulae used to calculate means, and station environment (Peterson et al., 1998, 1493-94, emphasis added).

To this list I would add changes in the basic paradigm of data collection across the history of meteorology. For centuries weather data was collected principally by individual observers. As national and military weather services emerged in the second half of the 19th century, they often created volunteer observer networks or incorporated existing ones; even today, volunteer and amateur meteorologists remain a mainstay of weather data networks in many countries (NOAA National Weather Service), such as the US Cooperative Observer Network of some 5000 stations. During this period international observing standards emerged — but gradually, in fits and starts, with inconsistent and incomplete adoption around the world.

As we will see, by the early 20th century forecasting and climatology had diverged. Most national weather services, focused on providing short-term forecasts, decreased their attention to the climatological aspects of observing networks. New observing stations often did not measure key climatological variables such as precipitation; existing stations made changes in instrumentation, location, and other factors, creating the temporal inhomogeneities (mentioned above) that reduced the climatological value of their data. The result was that only about one-fourth of stations in the US Cooperative Observer Network can meet the standards of the US Historical Climatology Network, consisting of stations which have provided "at least 80 years of high-quality data in a stable environment" (National Research Council, 1998). Therefore, today's climate scientists must engage in monumental efforts to reconstruct past data to meet modern standards. Standardization and automation have helped to reduce the effect of "non-climatic factors" on data collection, while modeling techniques have allowed climatologists to produce relatively homogeneous data sets from heterogeneous sources (Quayle et al., 1991; Karl et al., 1995; Easterling et al., 1996; Peterson et al., 1998). But it is impossible to eliminate these factors completely. Indeed, over the last decade or so, the temporal and spatial consistency of meteorological data has been undermined by both technological changes and reduction in the number of stations and platforms in the _in situ_ observing networks (National Research Council, 1999).

All infrastructures undergo change over time; this can produce not only quantitative but also qualitative effects. For example, today's climate information system collects _more_ information than in the past. Data for (say) 1890-1920 were produced by a much smaller, much less well-distributed network than data for (say) 1970-2000. In addition, however, today's data network collects new _kinds_ of information, such as those produced by satellite radiometers. These must be reconciled with data from older instrumentation (such as radiosondes and ground-based thermometers), a complex and often controversial task (Courain, 1991; National Research Council, 2000). Meanwhile, new data processing techniques allow old data to be reanalyzed (European Center for Medium Range Weather Forecasts, 1999; National Oceanic and Atmospheric Administration, 1999; Kistler et al., 2001). Reanalysis involves automatic quality controls that can, for example, revise original records to correct for systematic biases in instrument behavior. It also generates new data — or information treated as if it were data — about past atmospheric states by means of models which interpolate from actual instrument readings to points on computer model grids (National Research Council, 1991; Bengtsson et al., 2004). Thus not only does our understanding of the climate record change in time, but the climate record itself changes as well.

One possible reaction to this fact might be suspicion or mistrust. If the data themselves do not stay stable, how can we justify claims about climate change? Another, more sophisticated reaction — the one for which I will argue in this book — is to recognize that in the strange world of computational meteorology, raw data alone are rarely the best choice for understanding. Often, data sets produced by combining observations with artificial "data" synthesized by computer models are in fact more accurate. Modern weather models are able not only to check observations for errors and consistency, but also to combine numerous heterogeneous data sources and to interpolate missing data points. These synthetic data sets — produced by a technique known as "4-D (four-dimensional) data assimilation" — actually produce better weather forecasts than observations alone. Indeed, most modern weather forecasts are based on such "data" (National Research Council, 1991; Kalnay, 2003). Reanalysis injects a "frozen" 4-D data assimilation model with historical observational data for a long period (decades), producing "a result that could be more accurate and physically self-consistent than can be obtained from any one observing system" (U.S. Climate Change Science Program and Subcommittee on Global Change Research, 2006, 35). Reanalyzed climate data are currently regarded as highly problematic, due primarily to two factors: the many changes in the observing network over the last 50 years, and the biases of instruments types (such as radiosondes and satellites) against each other. Nonetheless, some scientists hold out hope that reanalysis will eventually generate canonical data sets, useable for climate trend analysis, that will be better than observational records alone.

These arguments suggest that the concept of "uncertainty" — whether in the traditional sense of an error bar surrounding an individual instrument reading, or in the more recent statistical sense of the standard deviation of a group of measurements — is far too simple to capture the complex relationships between data, models, and knowledge that exist in meteorology and climate science. Only a historical archeology of that relationship can provide a sufficiently rich perspective. Based on such an archeology, this book will argue that although many defects remain to be overcome (some of them quite serious), the meteorological information infrastructure's great age; its many iterations of standardization, quality control, and cross-calibration of instruments; and the sophistication of its computer models and model evaluations alllow it to produce trustworthy and reliable knowledge of global climatic change.

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