

# Virtual Infrastructure:

## Putting Information Infrastructure on the Technology Curve

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## Introduction

The present debate concerning the National Information Infrastructure (NII<sup>[1]</sup>) has focused primarily on the introduction of competitive markets for the supply and distribution of information. Although competition will be an important component of the NII, and one which we welcome, we argue that it is inappropriate to frame the debate entirely in terms of competition. Competition can be seen as a consequence of a fundamental development driving technical and economic innovation within the information industries; namely, the adoption of the digital paradigm.

The digital representation and transmission of information enables competition within the infrastructure. For example, competition within the US long distance telephone network is facilitated by software-controlled digital switches and cross-connect facilities. Competition has, in turn, accelerated the development of digital technology, thereby powering the present technology curve, the "perpetual engine" of the information age. However, digitization offers opportunities for innovation that go beyond competition. We hypothesize that the second, and more sweeping, wave of the digital revolution will emanate from the *virtualization* of the infrastructure. By a Virtual Infrastructure (VI), we mean the adoption of a software perspective that embraces a much more dynamic and heterogeneous approach to the representation of information, the configuration of hardware and software systems that process it, and the binding of resources to its processing and distribution.

In this paper, we offer a vision of what it would mean for the National Information Infrastructure to be a Virtual Infrastructure that takes full advantage of the digital paradigm. We begin by examining various distribution infrastructures - including traditional infrastructures for utilities and packaged goods as well as information. We point out differences among the commodities that these infrastructures are distributing, as well as differences among the infrastructures themselves.

We present a taxonomy of distribution models that could emerge for the National Information Infrastructure and describe the model we believe is the natural outcome. This model is substantially different from the "convergence model" that has been popularized by many NII pundits. In our model, the infrastructure is not only *competitive* - it is also *generic* and

*decoupled*. By generic, we mean that the distribution infrastructure can carry many types of information in much the same way as the roads can be used to deliver many types of packaged goods. By decoupled, we mean that the distribution of information is not vertically bundled; there are open markets in which information suppliers and information appliance vendors offer their wares independent of the distribution systems.

We then focus on the fundamental properties of digitized information and describe how they favor the proposed model. These properties include the ability to represent all digital information symbolically, and in a fundamental unit (the bit); the ease and declining expense of switching and converting the information being distributed; the ability to distribute information over a general-purpose, medium-independent network; and the software-based ability to defer the binding of resources until they are needed. Taken together, these properties enable a much more flexible, dynamic, and heterogeneous infrastructure than is currently being realized either in practice, in industry proposals [3, 4], or in proposed legislation [2, 5-9].

We explore several technical issues associated with the emergence of a virtual infrastructure, including:

- information appliances and software
- the mosaic of overlapping distribution networks
- the brokerage functions that match up suppliers, distributors, and customers

In our treatment of the technical issues, we identify heterogeneity as a key challenge facing computer scientists and make some specific suggestions for areas of investigation that might prove fruitful within the NII/VI context.

We conclude with a discussion of the policy implications of this work. We are particularly concerned with the identification of policies that foster innovation by reducing barriers to the insertion of new technology. Topics addressed include decoupling the regulation of information services from the regulation of information distribution, dealing with monopolies and vertical integration, and the publication of interface specifications.

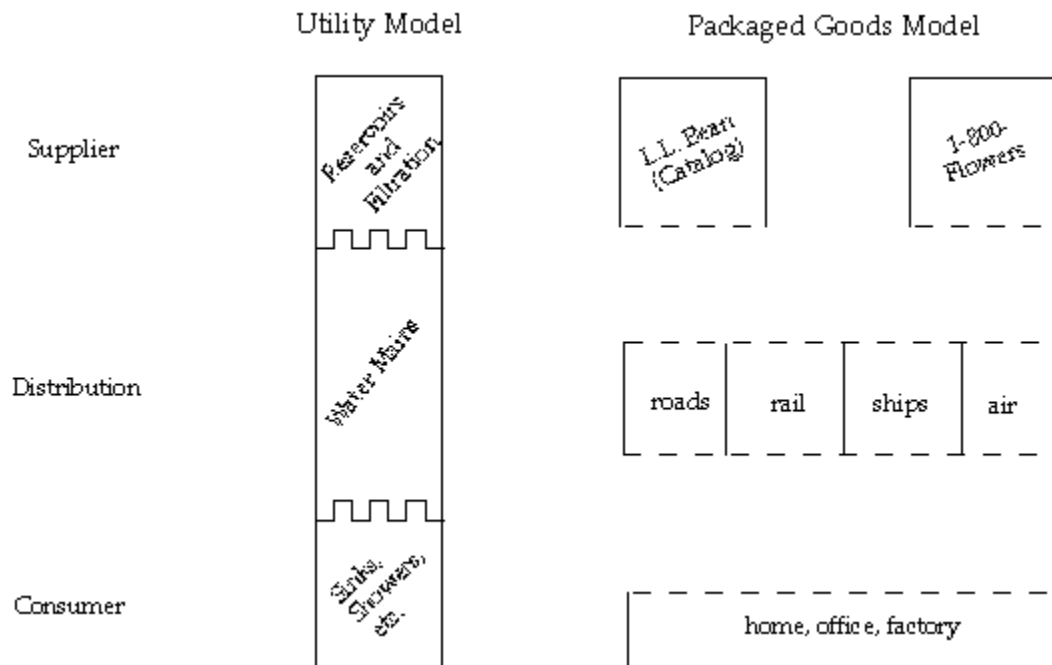
In presenting our vision of a Virtual Infrastructure, we are spanning the gulf between the computer science and technology policy research communities. We have tried to use (or define) terminology and a writing style that will be understood by both communities.

## **1. Traditional Infrastructures**

In this section, we discuss the organization of the present day infrastructures supporting public utilities, packaged goods, and information. We discuss each infrastructure in terms of vertical chains consisting of three components: suppliers (of goods or services), the distribution channels through which the supplies travel to reach their consumers, and the appliances through which the goods or services are consumed. These supply chains can be rigidly established or they can be dynamic, in which case brokerage functions may be used to match up the various components. In many infrastructures, such as packaged goods transportation, techniques such as composition and layering are used to assemble graphs or networks that are considerably more complex than the simple chains discussed here.

### 1.1. Utilities (Dedicated Distribution)

The traditional utilities - electricity, gas, and water - are vertically coupled, as illustrated by the water example in Figure 1. For each utility, there is a fixed supply / distribution / consumption chain, and each industry has its own dedicated distribution channel for which there is no competition. Because each of these industries is vertically coupled, the brokerage function is not needed.



**Figure 1. Traditional Infrastructures**

The specialized nature of these distribution channels makes sense given the different physical properties of the commodities. It is difficult to imagine electricity flowing over the gas lines, or gas flowing through the water mains. In the case of water, it is partly sheer volume that makes the dedicated distribution channel popular. It is possible to deliver water over a more generic distribution channel (e.g., by truck), but the amount of water needed would make this alternative unwieldy. Similarly, consumer appliances, such as toilets and toasters, are tailored to the physical properties of the commodity.

### 1.2. Packaged Goods (Generic Distribution)

The infrastructure for transporting packaged goods, including air, sea, and ground transportation, differs significantly from the infrastructure for utilities. In the packaged goods transport system, the distribution channel is *decoupled* from the supply chain and has the remarkable property that it can carry a wide range of commodities.

The key attribute of this network, which supports the *generic* delivery of goods, is that it is relatively inexpensive to repackage goods of a wide variety of shapes and sizes as they are distributed. Goods may be packaged, unpacked, and repackaged a number of times as they proceed from the supplier to the consumer, enabling them to be multiplexed, switched and

transported over the varying media (sea, air, rail, road, etc.). All of these goods share the cost of the distribution channel.

### 1.3. Current Information Infrastructure

The concept of an information infrastructure is not new. Although we currently have a rich information infrastructure, it more closely resembles the dedicated utility infrastructures (electricity, gas, and water) than the generic packaged goods system. For example, telephone and cable services are each carried over their own wired networks. Although radio and television share the airwaves, for practical purposes they are discrete distribution channels, since separate portions of the spectrum have been allocated to each type of service.

The resultant industry structure reflects this segregation; the information industries are, largely speaking, vertically coupled, as illustrated in Figure 2. For example, each television station has its own transmission facilities and its own portion of the spectrum - its channel. The same is true for radio. Similarly, the telephone company integrates telephone switching with the local distribution of telephone wires and the cable company bundles its transmission network with program packages. Within the home or business, we also see the separation of the appliances that are used with each distribution channel - radio, television, telephone, etc. Each channel has its own discrete types of appliances that are, largely speaking, not interoperable with other channels.[2]

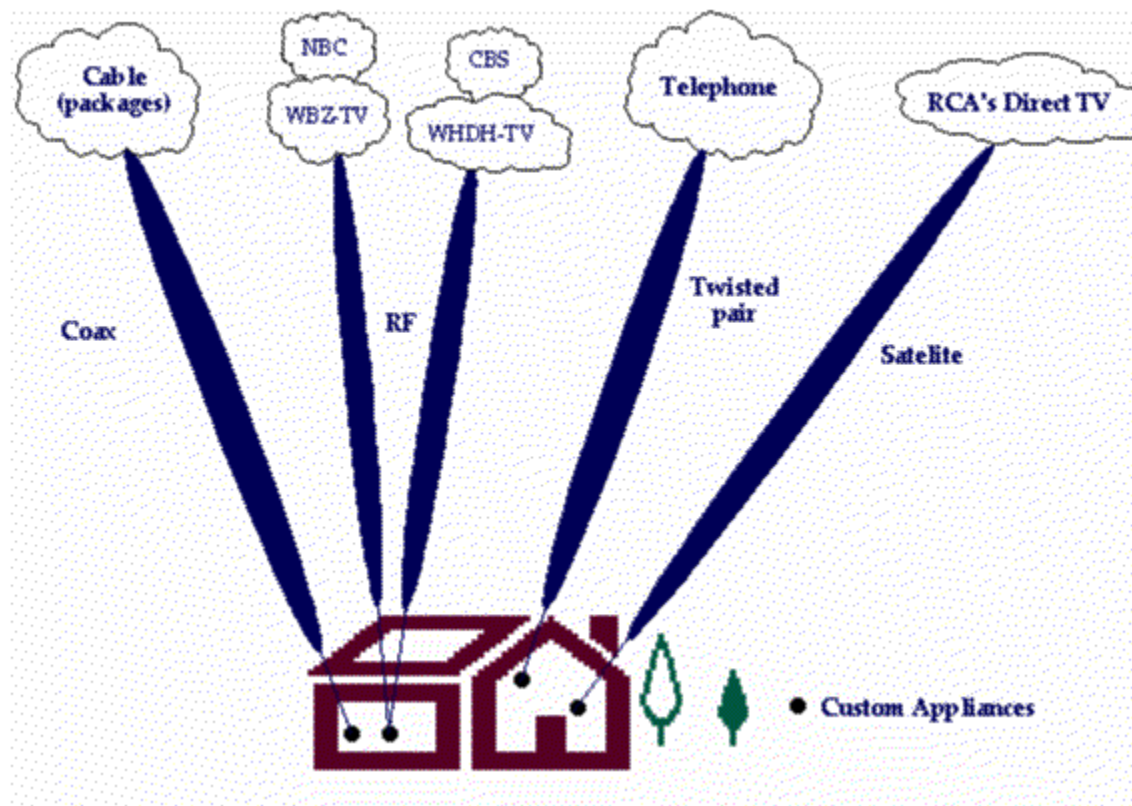


Figure 2. Traditional Information Infrastructure

Within each of the vertically structured information infrastructures, it is difficult to engender a

climate of rapid innovation - the tradition of homogeneity makes it difficult to introduce a second or third technology for the distribution of a given type of information or to introduce a new type of information to an existing distribution substrate.

### 1.4. Convergence

The present belief that competition is the driving force shaping the information industries is leading towards the *convergence* model (Figure 3). In this model, large alliances of distributors (network providers) and suppliers (content providers) compete with each other [10]. Each alliance will offer consumers the opportunity to purchase bundled (i.e., vertically coupled) information services. Within each geographic region, alliances are forming around the traditional telephony and cable distributors. However, each of these alliances is leveraging digital technology to implement a generic infrastructure that can supply and deliver a wide range of information services.

Although the convergence model is generic, the vertical coupling between suppliers and a few distributors is not necessary, nor is it an innovative means of leveraging digital technology. It is not necessary because there is no physical characteristic that places a small limit on the number of feasible distribution channels; digital channels need not consume large amounts of physical space (as roads or water mains do). There is "room" for many distribution channels, both wired and wireless, to enter a customer's premises.

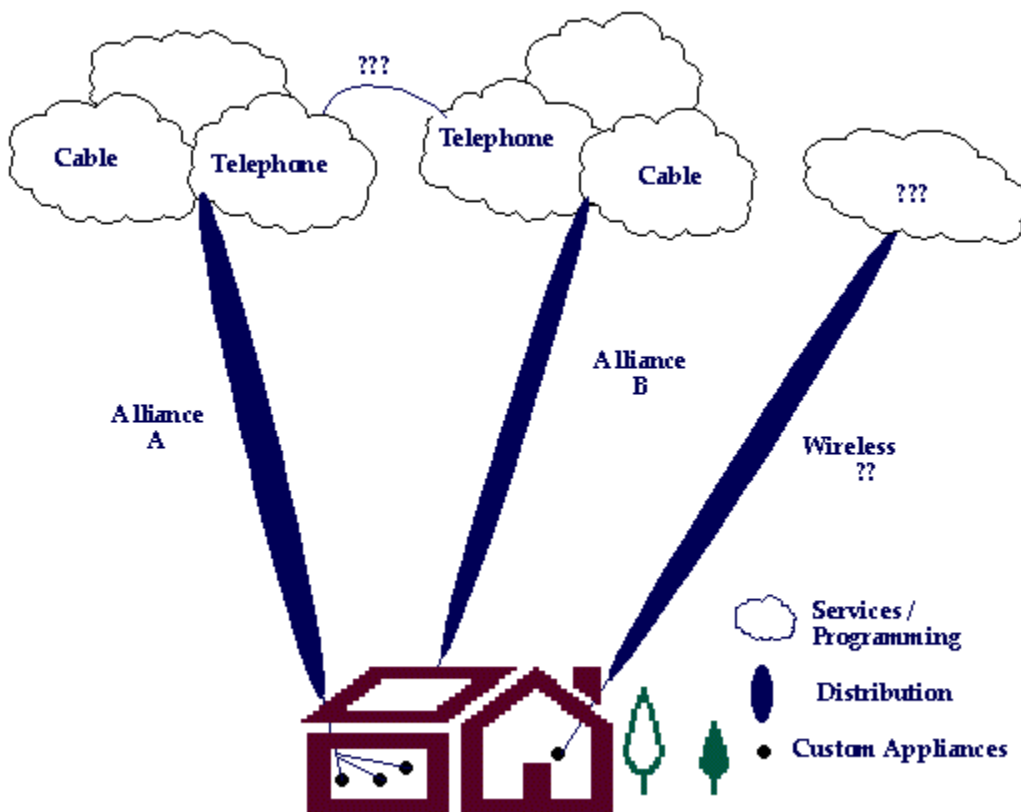


Figure 3. Convergence-Driven Infrastructure

The convergence model is not hospitable to innovation because it artificially limits the degree and dynamics of competition and choice. The supply chains will be relatively fixed, with consumers subscribing to bundles of information services on a month-to-month basis. Although competition may exist at the national and metropolitan level, individual neighborhoods and houses may not have access to multiple alliances - at least not on a dynamic (e.g., minute-to-minute) basis. Furthermore, the mechanisms and transaction costs associated with interoperation across alliance boundaries are likely to discourage competition and choice on a per transaction basis. The convergence model of information distribution may well be generic and competitive, but because it is not decoupled, it is not innovative.

### **1.5. The Coupling of Supply and Distribution**

The vertical coupling of distribution with supply is not the ideal. A company in the business of supplying goods or services is not inherently interested in being in the distribution business or in being captured within a large alliance. Most suppliers view distribution as a necessary evil, and if they can rely on a decoupled distribution mechanism, they will. Why then do vertically coupled infrastructures exist (beyond the physical reasons noted above)? We believe they exist because safe, cost-effective, decoupled channels are not available.

Decoupled distribution channels must be *safe*. There must be no danger that the means of distribution will be captured by one competitor and the others will be starved out or acquired. A safe channel must also have ample capacity. If there is a danger that a company will not be able to move enough goods fast enough over the channel, it will not be considered safe. This means that there must be considerable competition within the distribution market. Ideally, the distribution channels will not just be shared among a single group of competing suppliers (sharing with your competitors is far from safe). The channels will also be shared with other groups of suppliers, who compete for the supply of different types of good or services. Therefore, decoupled channels must also be generic.

The package transport infrastructure satisfies these criteria for a safe, decoupled distribution channel (even though parts of it are not competitive). It is used by many competitors in many areas; it is also used by the government and private sector. There is no danger of a single supplier taking over the system and starving anyone out. The system also has enough capacity for most users' purposes. Even if demand for a supplier's goods quadruples unexpectedly there is likely to be a way for those goods to be distributed.

### **1.6. Toward a Competitive, Generic, Decoupled Information Infrastructure**

We believe that the *natural* consequence of digital technology will be the emergence of an information infrastructure that is not only competitive, but also generic and decoupled. Such an infrastructure is illustrated in Figure 4. Rather than supporting competition between a few vertically coupled alliances, this organization supports widespread competition in all links of the chain - supply, distribution, and consumer appliances. The infrastructure we envision is also *virtual*, in the sense that it appears to simultaneously support an unlimited number of alternative supply chains. In practice, a limited but large number of supply chains are dynamically assembled as required, possibly on a per-transaction basis. Not only are there more competitors at more levels, the pace (or frequency) of competition is considerably faster. In particular, the

distribution channels are interchangeable, in the sense that one channel can be used in place of another. The emergence of such a virtual infrastructure will be a consequence of the fundamental properties of digital technology, especially its software-based flexibility and the declining cost of conversions between different representations of digitized information. In Section 3, we show how a competitive, generic, decoupled information infrastructure leverages these fundamental properties.

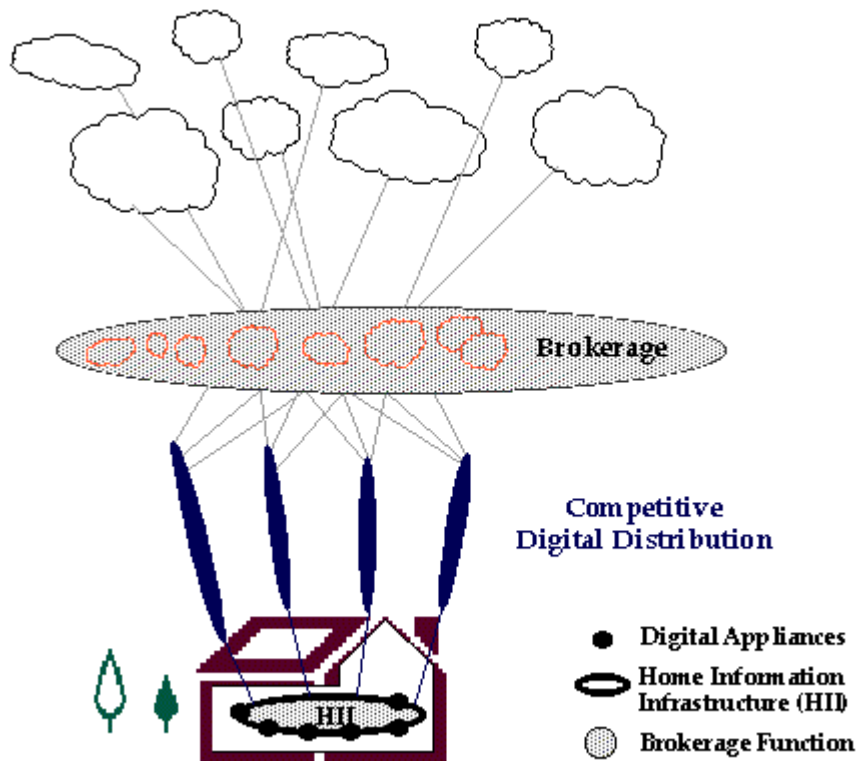


Figure 4. Virtual Infrastructure

## 2. NII Architectures: A Taxonomy

In this section, we present a taxonomy for the comparison of alternative national information infrastructures. We map current and planned architectures into this taxonomy and discuss how they evolve over time.

### 2.1. NII Taxonomy

Our NII taxonomy is based on the three infrastructure properties discussed in the previous section: competitive (C) versus monopolistic (~C), generic (G) versus specialized (~G), and decoupled (D) versus bundled (~D).

- In a competitive infrastructure (C), the supplier and consumer have a choice of distribution channels; in a monopolistic infrastructure (~C), only one channel is available (for each type of service).
- In a generic infrastructure (G), the distribution channel can handle many different types

of information and services; in a specialized infrastructure (~G), the distribution channel is tailored to one type of information.

- In a decoupled infrastructure (D), the distribution channels are decoupled from the suppliers; each channel provides distribution for many competing suppliers. In a vertically coupled infrastructure (~D), the distribution channel is bundled with suppliers - it only provides access to one (or a few) suppliers of each type of goods or services.

Although these three characteristics are not entirely orthogonal, they provide an effective means for dividing the infrastructure architecture space into eight possible states. These cases are summarized in Table 1 and described in more detail as follows:

Infrastructure	Competitive	Generic	Decoupled
Utility: Cable, old AT&T Monopoly			
Analog: Radio, TV	✓		
MFJ: Local access to long-distance telephony			✓
??? (not stable)	✓		✓
Convergence	✓	✓	
De Facto Monopoly: Vertically integrated		✓	
"Born Again" Monopoly: Roads, US Mail		✓	✓
CGD: Package Transport (Rail, Air, etc.)	✓	✓	✓

**Table 1. CGD Taxonomy**

~C~G~D. This is the utility state. It is monopolistic, specialized, and vertically bundled. Examples are the cable industry and traditional utilities, including the phone system before it was broken up. Complete vertical integration of distribution and service is so commonplace that it is often taken for granted as a necessity of building and operating a distributed service.

C~G~D We refer to this as the analog state. Examples of competitive, specialized, bundled infrastructures are radio, broadcast television, and the pre-AT&T competitive telephony industry. Due to economies of scale, this infrastructure may lead to a natural monopoly (~C~G~D) unless the start-up costs are low, as is the case with air waves (where little physical infrastructure need be built).

~C~GD. We refer to this as the MFJ state.[3] It is a monopolistic, specialized, decoupled infrastructure in which competing same-service providers share a monopoly distribution network. The quintessential example is the regulated "equal access" to local telephone networks that enables competition among the suppliers of long-distance telephony services. Until recently, decoupling has been enforced by barring the distributors from competing with the suppliers. The interface between the monopoly distributor and the competing suppliers is critical in making this model work.



**C~GD.** We have not identified any good examples of competitive, specialized, decoupled infrastructures. We believe that this state is not stable because a decoupled infrastructure based on specialized distribution does not meet the safety criteria discussed in Section 1.5.[4]

**CG~D.** This is the convergence state - a competitive, generic, vertically bundled infrastructure. It is emerging as the digitization of information and its distribution channels makes the channels interchangeable. Competition can be viewed as a side effect of a process in which a multiplicity of previously segregated information utilities each deploys a digital distribution substrate. It is also enabled by software, which provides the ability to support network interoperation and features essential to competition, such as telephone number portability. Examples of convergence models currently being planned are an alliance between a cable company and a telephone company, which would offer "full service networks" in competition with other such alliances.

**~CG~D.** This is the de facto monopoly state. It is a monopolistic, generic, integrated infrastructure that could well be the interim result of present convergence efforts (see Section 2.2 and Figure 5). A historic example is the rail road "robber barons" who had a de facto, unregulated monopoly.

**~CGD.** This is the "born again" regulated monopoly. In this state, competing suppliers share a generic monopoly distribution network that is held in check and decoupled from the suppliers by regulatory forces. This model also applies to the relationship between the local roads system and the higher levels of the packaged goods infrastructure - there is only one local road leading to a given address (monopoly), but many types of goods can travel over that road as long as they are packaged, and many different suppliers deliver goods over the same local road.

**CGD.** This is the competitive, generic, decoupled state that we believe would naturally emerge in the absence of the historic artifacts that presently surround the information industries. In this state there are many overlapping distribution channels. Each channel supports the distribution of a wide range of services and provides access to competitive suppliers of each type of service. An example is the package transport system as a whole (rail, air, etc.).

## 2.2. Transition Scenarios

To take a long term (i.e., forty year) perspective, we model information infrastructure as a process that transitions from state to state. Some of the states in our taxonomy are not stable and others are meta-stable; that is, they may last for a while but over time they lead into other states. We are concerned with the possible end states of the process and how the process might be accelerated.

Figure 5 depicts the transition process we are presently embarked on, starting from the three states that were stable circa 1990:

- The digitization of the distribution substrate is driving the present utility (**~C~G~D**) and MFJ (**~C~GD**) infrastructures towards the convergence state (**CG~D**). The analog suppliers may merge into the convergence alliances.
- The convergence state may last some considerable time. However, in the absence of ongoing innovation, economies of scale will create a natural monopoly and drive **CG~D**

towards  $\sim\text{CG}\sim\text{D}$ , at least at the level of individual geographic regions, if not nationally and globally.

- The real or perceived abuse of power associated with  $\sim\text{CG}\sim\text{D}$  will lead to anti-trust actions and the eventual emergence of a born again regulated monopoly ( $\sim\text{CGD}$ ).

If this scenario is allowed to proceed, the regulatory wheel will eventually (e.g., by 2020 or 2030) turn full circle, though, owing to its generic scope, the new monopoly will be far more powerful and resistant to innovation than those that have come before it. The convergence, de facto monopoly, and regulated monopoly states will inhibit the cycle of innovation and competition that powers the technology curve's perpetual engine. Over the long term, pent-up innovation will form a *bubble* that will weaken and ultimately burst the monopoly. The bad news lies in the forty years of lean innovation that might intervene.

We believe that the path leading through convergence and monopoly can be shortened or avoided altogether. Innovation and competition are mutually supportive and the continuous insertion of innovative technology can be used to offset the economies of scale that would otherwise lead to natural monopoly. In a regulated monopoly, carefully crafted interfaces attempt to simulate competition [11]. Instead of trying to simulate competition, we should favor the real thing: a competitive, generic, decoupled infrastructure that supports a high degree of innovation and competition.

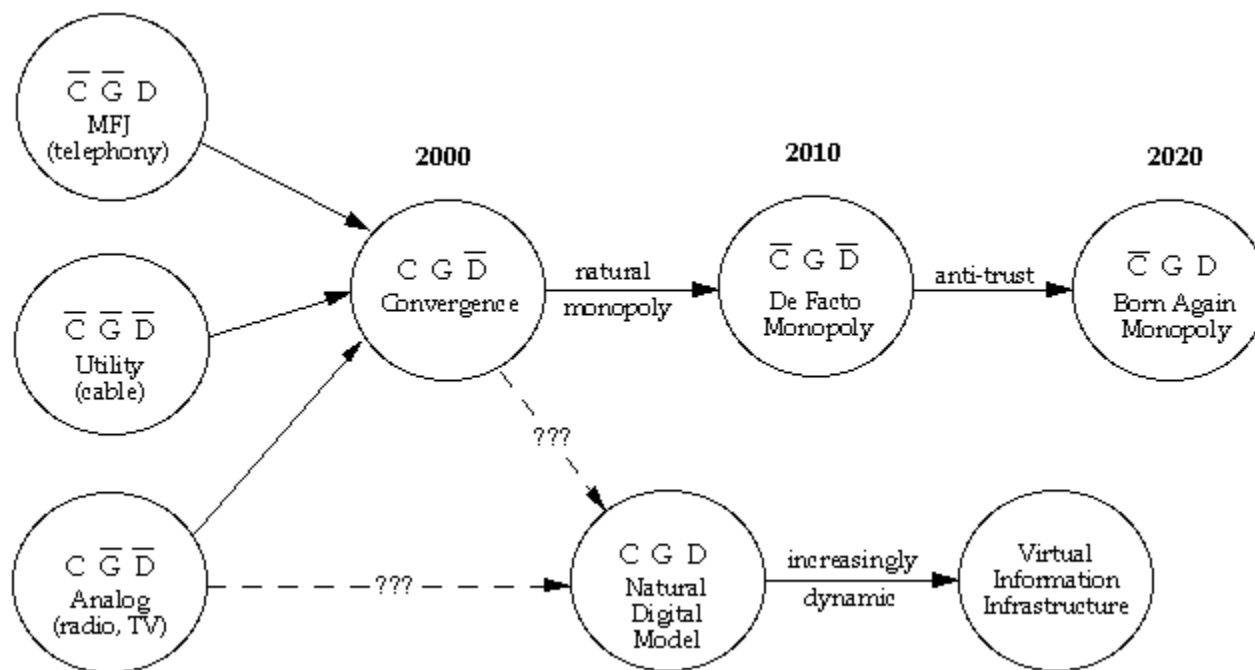


Figure 5. Transition Scenarios

### 3. What's Different about Digital Information?

Digitized information has certain properties that make it different from any other type of commodity. The properties of digitized information and distribution channels that favor **CGD** infrastructure are summarized in Table 2 and discussed below. (This set of properties is not

orthogonal.) Some of these properties enable functions that can be performed in software. This is particularly important to the *virtualization* of the infrastructure.

### 3.1 Digital Fundamentals

This section describes the relevant properties of digitized information - symbolic representation and conversion, encapsulation and fragmentation, temporal decoupling, and dynamic resource configuration and allocation.

**Symbolic Representation and Conversion.** Information is not a physical commodity. It can be represented symbolically; for example, by sequences of 0s and 1s. Information can be represented in many forms and distributed over many different media, including non-physical media such as the radio spectrum.

There is clearly room for many digital distribution channels - the free space spectrum is already shared; and fibers, unlike roads, occupy so little volume that a single conduit has room for many of them. Utility distribution networks, such as water mains or local roads, are fundamentally different: for these, space limitations and the physical inconvenience of digging up the streets dictate local distribution monopolies.

An important aspect of symbolic representation is that it is possible to convert between different representations. Coding, such as for error detection, can be done to suit the channel. Translations to address appliance incompatibility are also possible; for example, information originating from US telephones is routinely translated into a different format suitable for European telephones.

**Encapsulation and Fragmentation.** Sequences of bits (e.g., packets whose start and end can be identified) are the digital equivalent of packages. An especially powerful conversion operation involves the encapsulation of information within packets. Since the packets are opaque to the distribution channels, they can be used to transfer any information that is represented symbolically. As is the case with package transport, digital packets can be arbitrarily nested and repackaged, allowing flexible switching and multiplexing. However, the cost of this digital "packaging", measured in processor cycles and storage, is declining steeply.

Unlike physical goods, an item of information represented by a lengthy sequence of bits can easily and cheaply be fragmented into many smaller sequences that can be re-arranged during distribution and eventually put back together to recover the original form. (This could in theory be done with physical goods, too, but not without great expense. Much of the value of a forty story building, for example, is in its assembly. Furthermore, it is not possible to fragment and reassemble some items at all, such as people.)

**Temporal Decoupling.** There need not be any fixed timing associated with the bits representing an item of information. The individual bits can be transmitted at any speed; for example, they can be stretched or compressed, and the time between bits can be varied. If the timing of the bits within a sampled signal is important, that timing can be represented digitally and encoded within the digital sequence. This property supports the decoupling of supply, distribution, and consumption by allowing different components in the chain to operate at different speeds. For example, a sequence of bits may be squirted at high speed into a

distribution channel, delivered at low speed to the consumer's premises, and played out by the appliance at a rate that is suited to the user. In conjunction with conversion, temporal decoupling also facilitates generic distribution by allowing different types of information, sent at different rates, to be transmitted over the same distribution substrate.

Implications	Digital Fundamentals					
	Symbolic representation	Conversion	Encapsulation	Fragmentation	Time independence	Dynamic resource allocation
Competition & Innovation	✓	✓				
Generic distribution	✓	✓	✓	✓		
Decoupling supply/appliances	✓	✓	✓	✓	✓	✓

**Table 2. Digital Properties**

**Dynamic Resource Configuration and Allocation.** Information processing and transmission resources can be dynamically configured and allocated. Dynamic configuration allows resources to be tailored to the requirements of a particular transaction. Programmable resources, such as general purpose processors, are examples of configurable resources.

These properties, especially when exploited by software, enable *virtual* supply chains that have the appearance of always being available, yet only consume resources when they are used. These properties are related to the technology curve in two ways: the decline in the transaction overhead associated with dynamic configuration is tied to the declining costs of processors and memory; and with increasing processing power comes the ability to execute software that configures and allocates distribution resources at a faster rate and in more complex ways.

### 3.2. Observations

The following observations follow from the properties of digital information and the operations that are enabled:

**Medium independence and generic distribution.** Information can be represented in many forms and distributed over many different types of distribution channels. Encapsulation, fragmentation, and temporal decoupling allow the channels to be generic; that is, they can carry a wide range of services rather than be tailored to a single service. From an architectural perspective, digital distribution channels (as opposed to the bits they deliver) are completely interchangeable; any type of digital information can flow over any type of channel[5]

**Composition.** The many types of distribution channels can be transparently composed into complex networks through concatenation and hierarchy. Concatenation leverages the

conversion and temporal decoupling properties. In conjunction with digital memory, it is possible to concatenate networks running at different speeds. Suppliers and consumers have the impression of a ubiquitous, seamless, and continually accessible distribution network. Although concatenation and hierarchical embedding are not unique to digital environments, their use is greatly assisted by conversion, temporal decoupling, and the software-based ability to dynamically configure and allocate resources.

**Appliance independence.** Subject to the availability of suitable adapters (converters), the same information appliances can be used with multiple distribution channels and information suppliers. This is a consequence of the conversion property. There will also be many different types of appliances, some generic and some specialized. However, the latter will be tailored in accordance with the users' functional requirements rather than those of the supplier or distributor. This property of digital information distinguishes it from the utilities: a gas stove can't be used with the electricity network.

### 3.3. Opportunities

The properties of digitized information lead to unique opportunities for the creation of a competitive Virtual Infrastructure that will support rapid innovation over a sustained period. A key driver is that the cost of processing power and memory are declining, resulting in declining cost of conversion and its related properties. The shrinking cost of conversion has established a trend towards an increasingly heterogeneous infrastructure.

Another driver, which is also tied to the processing and memory technology curves, is the ability to dynamically allocate and configure resources. Systems are increasingly built of virtual resources, which are emulated through software that dynamically allocates and configures the underlying assets. As infrastructure software becomes more pervasive and is implemented on higher performance platforms, the allocation and configuration of resources become more dynamic; for example, the number and frequency of allocation and configuration decisions increases.[6] Furthermore, once a resource has been *virtualized*, the process through which it becomes more dynamic is institutionalized - the frequency of decisions scales with the underlying technology.

## 4. Realizing a Virtual Infrastructure

How do we move toward a virtual (that is, CGD) infrastructure from the relatively fixed and vertically integrated world we live in today? The most essential step is a shift in mindset; we need to begin thinking of the virtual infrastructure model as our ultimate goal. We believe that the properties of digital technology will lead us to that goal if a few technical and policy challenges are dealt with appropriately. Later in this section, we present some of the technical issues relating to VI, culminating in the pivotal technical challenge - the mastering of heterogeneity. VI policy considerations are discussed in Section 5.

### 4.1 Roles versus Capacity

VI supply chains are not static nor are VI users exclusively suppliers or consumers of information. The terms "supplier" and "consumer" correspond to *roles* that a VI user may take

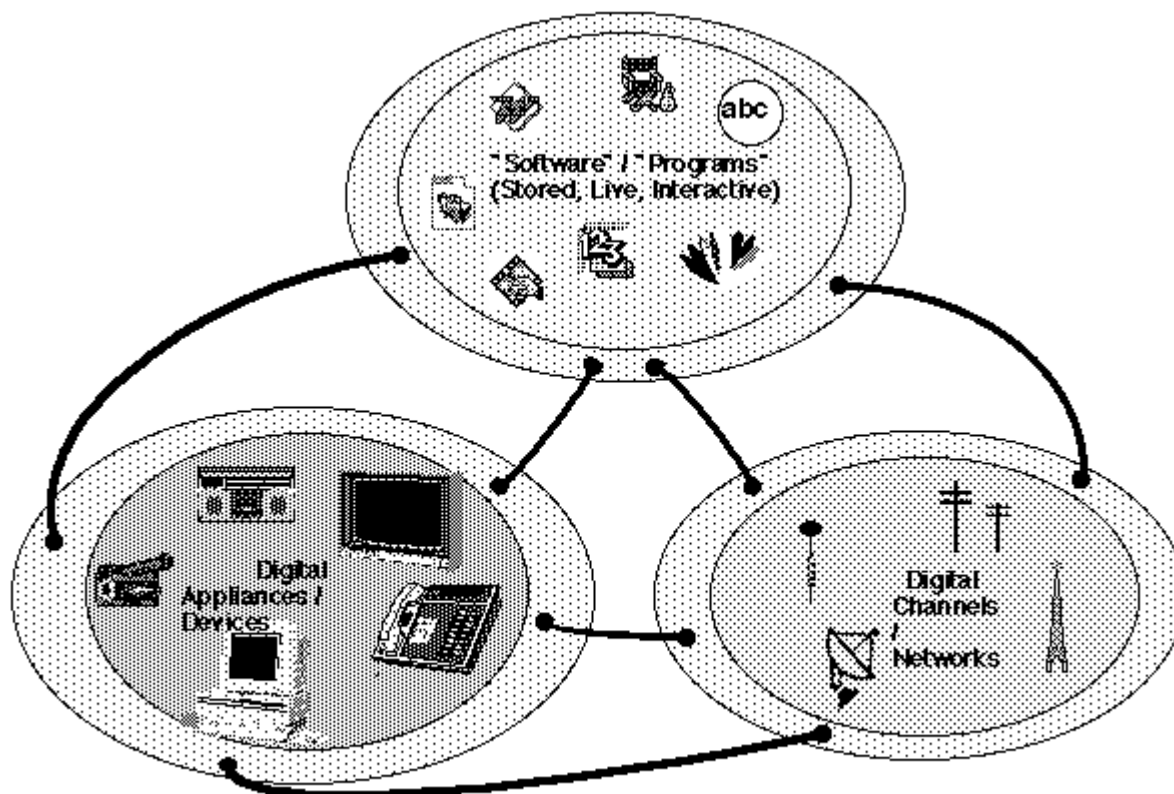
on for the purposes of a given transaction. A VI user may participate in any number of simultaneous supply chains, taking on different roles within the context of each chain.

It is easy to conclude that there are a relatively small number of high volume information suppliers providing services to an immense number of comparatively low volume consumers. However, this is not true today and will be even less so in the future. Organizations such as cable programmers consume large volumes of information from many sources and supply it to large numbers of clients. There are many independent suppliers of information, including authors, freelancers, and editors, who work from small business premises and homes.

The appropriate distinction is not between suppliers and consumers, but between high and low volume *users* of the infrastructure. Large (high volume) users will have sustained requirements for high capacity appliances and channels. Although small (low volume) users, on average, will have more modest needs, they will still have instantaneous requirements to supply and consume information at high rates. Thus the distinction between large and small has more to do with average capacity than instantaneous usage.

## **4.2. Supply Chain Dynamics**

The VI is dynamic, scalable, and extensible - its design assumes continuous deployment, migration, and renewal. Unlike a fixed structure that is built and then used, the VI is based on a collection of reusable infrastructure building blocks, or components. VI supply chains are dynamically assembled from these components, which include appliances, communication channels, and software (Figure 6). Thus realizing a VI involves the virtualization of these building blocks and the means for their dynamic binding into chains. We refer to the latter function as "brokerage."



**Figure 6. VI Building Blocks / Components**

Brokerage plays an important role in a competitive interoperable infrastructure. Components at all levels of the infrastructure cooperate in the dynamic composition of supply chains, and brokerage functions are the glue that facilitates the interconnection of the components. These functions provide *market* and *configuration* services. In a market environment they support dynamic choice and arbitrage. Brokerage also permits the aggregation of small users into larger pools, providing them with access to information and distribution services that are purchased in bulk, divided into smaller units, and resold. Taken together, these services provide the liquidity that enables competition and lowers the barriers to entry and innovation.

Brokerage configuration services control and configure the points of conversion at which information is transformed from the service-specific form in which it is produced/consumed to formats that are compatible with the chosen distribution channels. These configuration services are essential to the dynamic creation of VI supply chains.

Brokerage functions may be provided by people, implemented in software, or achieved through some combination of both. The functions may be fully embedded within, and controlled by, user software or they may be controlled by independent third parties. Although the brokerage functions exercise control over VI components, they can do so remotely; that is, they need not be collocated with them nor does the data flowing between supplier and consumer need to pass through the brokerage elements.

### 4.3. Virtual Appliances

Between the users of the VI and the distribution channels are the appliances that handle digital information; for example, telephones, VCRs, televisions, and computers. Currently these appliances are used with specific services and specific types of distribution channels.

In the VI, two types of information appliances are likely to emerge. Some appliances will be generic; they will be used for a wide range of information services. These are similar to today's personal computers, laptops, and workstations. Other appliances will continue to be specialized for the manipulation of a specific type of information, such as music. The bulk of these virtual appliances, especially the generic ones, will be role independent (i.e., they will be able to take on both the supplier and consumer roles). However, specialization and role dependence will make sense in cases where the appliances can be produced for an extremely low price and distributed about the home and workplace in large numbers, in much the same way as clocks, radios, and CD players are today.

The truly exciting breakthrough, waiting to happen, is the digitization of the interfaces to these specialized appliances. Over the past decade the internal workings of these appliances have become increasingly digital and software-based. However, the interconnection of appliances is largely analog. As the digitization process continues, we can expect to see the emergence of interfaces that support the digital interconnection of appliances based on local networks, such as LANs.

For example, within the home one might find a local area network (wired or wireless) to which generic appliances such as personal computers and specialized appliances such as CD players, digital VCRs, televisions, phones, and so forth, are attached. These appliances would be able to interact over the network; for example, one might be able to edit home videos on the personal computer or access music stored in a file server from any audio player in the home.

#### 4.4. Virtual Channels and Networks

Some traditional distribution networks, such as television and cable, are largely asymmetric and fixed. They support the dissemination of services from a central distribution point to a large number of consumers. Others, such as telephony, provide users with communication channels that are not only bi-directional, but also configurable (e.g., switched). Typically, a *bearer* channel is formed through the concatenation of a number of *real* channels, which may be carried on an enclosed medium, such as fiber or copper, or through the free space spectrum. The channels may be shared, through the multiplexing of multiple bearers on a single real channel. Switching permits the real channels to be dynamically configured so that they can support different combinations of bearer channels supporting communication among different users.

**Digitization.** Over the years, many of the real channels buried within these networks have been digitized. This process has been cost-justified through improvements in the price and quality of supplying analog bearer services. The onward march of digital technology has now reached the point where this cost argument applies to almost all real channels, including those that traverse the "last mile" to the premises of the consumer. Through digitization, cable and wired telephony see the potential for improved quality and reduced maintenance costs. The cellular telephony and broadcast television industries can benefit through more efficient use of the spectrum.



**Virtualization.** As the last mile is digitized, bearer channels that are digital and of high capacity become feasible. More importantly, the configuration of these channels can also be far more dynamic, leading to a *virtualization* of the distribution substrate. This substrate will provide the appliances, and their users, with the *appearance* of being simultaneously connected to a large number of peers. Instead of using one bearer channel at a time, they can gain access to a large number of virtual channels that share their point of attachment to the distribution system. Furthermore, the capacity of the individual bearer channel is not fixed, but can vary from zero to the limits imposed by the concatenated real channels and appliances. Typically this is accomplished by dynamically multiplexing and switching the real channels on a fine grain basis. In digital terms, this means leveraging the conversion, temporal decoupling, and dynamic resource allocation properties of digital technologies.

**Concatenation.** The VI's distribution substrate is a network of networks that includes wireless (TV, cellular, radio), fiber optic, coaxial cable, twisted pair, etc. Within their own premises or campus, users can operate private networks, shared only by their own appliances. Between premises, users contract to use shared infrastructure, possibly in the form of predefined virtual private networks, but often on a more dynamic basis.

The private and shared networks are concatenated together so that the combined substrate appears as one ubiquitous, continuous network to its users. Digital conversion supports the interoperation of decoupled components and brokerage functions enable competition at many levels. Users can choose among distribution channels, which rely on different technologies and may have different properties of delay, error correction, etc.

**Large and small users.** As previously discussed, it may be appropriate to distinguish between large and small users, rather than between suppliers and consumers. We believe that different distribution vendors will emerge to cater to *pools* of users with similar distribution requirements. Although many different types of pools may emerge, the discussion which follows arbitrarily distinguishes between pools of large and small capacity users.

**Small users.** Low volume users present a less attractive market for vendors, especially those using enclosed spectrum technologies, such as fiber and copper, which require the installation and maintenance of assets that couple the user to the distribution system. Distribution vendors have adopted a number of *optimizations* to offset their costs, including asymmetry, sharing, and sharply limiting instantaneous capacity.

Television and traditional cable are good examples of highly asymmetric systems that leverage sharing by broadcasting the same signal to a large geographic area. The difficulty with this arrangement is that it is unidirectional and the capacity of the single broadcast channel limits the vendor's aggregate capacity.

On average, small businesses and homes will consume more information than they produce. However, if they are precluded from transmitting information then they are precluded from acting in the supplier role. In fact, the situation is somewhat worse - if the small supplier is incapable of sending out large bursts of information from time to time, then they are effectively precluded from competing in many VI markets. In short, small users require access to virtual channels with similar capabilities to those made available to large users. The pooling of small

users through cellularization and the dynamic allocation of shared resources provides the means to resolve this dilemma.

**Cellularization.** A common optimization is to pool users based on geographic locality so that they can maximize the sharing of physical assets. For example, users residing in a large building might benefit from an arrangement in which they are serviced by a single fiber. This form of geographic pooling is common in wireless telephony, where base stations are established to service each neighborhood *cell* and a portion of the RF spectrum is dynamically shared among all of the users within the cell. The channel's interconnecting base stations are also shared, irrespective of whether they are implemented through wireless or wired means. In effect, all of the physical assets are shared among pool users. Although present cellular systems only support fixed and limited capacity bearer channels, they are likely to be virtualized in the future.

Telephone systems are also being cellularized to improve sharing and reduce the maintenance costs of the distribution plant. High capacity fibers are run to each neighborhood, where they are connected to the individual twisted pairs that service each home. This is a less satisfying solution than the wireless case - the fiber plant is shared, but the twisted pairs remain dedicated to individual subscribers. Furthermore, the bandwidth limitations of these pairs place fixed and relatively low limits on the capacity available to each user.

Finally, we note that the terrestrial broadcast of television signals is also adopting digital techniques. To avoid interference with existing analog signals, digital television is likely to adopt low power techniques involving multiple transmitters, each of which covers a reduced geographic area. This might well be a first step towards the cellularization of television, through the transmission of different signals in different neighborhoods.

In summary, cellularization provides a sharing mechanism through which virtualized distribution can be made available to pools of small capacity users. In Section 5 we discuss how to safeguard competition within these markets.

**Cross-connection.** A further market for distribution vendors will be in the cross-connection of vendors. For telephony, this role is presently played by the long distance carriers, who provide cross-connection among the regional telephone companies, both wired and wireless. In terms of physical assets, this market is similar to the large user market. Traffic from the small users is aggregated by their access networks and presented for cross-connection at a relatively small number of high capacity points of presence. Although the vendor requires additional capabilities, such as the ability to bill large numbers of users, these services can be procured through third parties. Accordingly, we believe that these markets will engender the same vigorous and innovative competition as the large user markets.

#### **4.5. The VI Challenge - Mastering Heterogeneity**

The Virtual Infrastructure is heterogeneous in many ways - many different services, representations of information, protocols, and types of appliances coexist. To be successful, the VI must not only accommodate heterogeneity, but embrace and master it. Heterogeneity is desirable, and inevitable:

- Heterogeneity is desirable because it enables competition and innovation. If the information infrastructure is set up to handle heterogeneity, it is easier to insert new and innovative technologies.
- Heterogeneity within the NII is inevitable and the process has already begun. Since divestiture, each regional telephone company has been planning its own architecture. This has long been true for the cable companies, where the situation is aggravated by geographic dispersion of their holdings. Residents of adjacent towns are often served by different operators who provide access to different packages through settop appliances that are not interchangeable.

In the past, large systems, such as the telephone network, have been tailored to the support of a single dominant service and have been relatively homogeneous in their implementation. However, the future lies with heterogeneous environments in which many different technologies support a wide range of services. The mastering of heterogeneity is a crucial step towards a dynamic infrastructure that supports rapid innovation, both in the services that are offered and in the underlying technologies through which they are implemented and distributed.

To be successful, the VI must push software technology beyond its present limits, especially in our ability to mask the complexity associated with heterogeneity. However, computer scientists have been trying to address this problem for quite some time and progress has been slow. Rather than solve the generic problem, we have identified the following specific NII/VI objectives, towards which concrete steps might be taken:

- Digital labeling of all VI objects
- Dynamic management of appliance and channel configuration
- Tools that support the publication of interfaces
- The development of sophisticated conversion technology

**Labeling.** A software-accessible NII label should be attached to every software object [7] appliance, and channel. The label should provide the name and type of the component. This is analogous to physical labels that provide the serial number and model of appliances and software. ASN.1 object identifiers [13] are examples of an existing labeling scheme that could be used for this purpose and [14] describes their application to motion pictures and television programs.

**Configuration management.** A customer should be able to buy an appliance, plug it in (or not), and expect it to work with whatever surrounding infrastructure is available. The configuration may be achieved by customer managed software or through a service provided by another party. The Macintosh chooser has a glimmer of this functionality - when a printer is powered up and attached to the network the software automatically detects it and adds it to the list of available printers.

**Publication of interfaces.** An NII label allows a user to identify the model, or type, of a component. Given this information, one should be able to obtain a specification of its interface. The interface can be specified in a number of ways:

- Well-known standard. The label could identify an international standard to which the component's interfaces conform.

- Published interface. The interface may be specific to the vendor of the appliance, channel, or software. In this case, the label identifies the published specification. (For example, the label could supply a World Wide Web URL through which the specification can be accessed.)
- Self-describing. The component may be able to render its own specification through one of its own interfaces. In this case, the label must identify the means by which this interface is interrogated; that is, the specification to which it conforms. (Of course, this is a recursive process which must ultimately be bounded through the use of some well known specification.)

Typically, the user will simply examine the label and note that it identifies an interface that is already familiar. The user need only obtain and process the specification for new types / versions of components. Of course, there will be a heterogeneous mix of labeling and interrogation schemes. For example, each resource could have an associated Management Information Bases (MIBs) that could be interrogated using the Simple Network Management Protocol (SNMP). Microsoft's IUNKNOWN interface to OLE components [15,16] and CI Labs OpenDoc/OSA [17,18] might provide similar functionality. A first step is to reach high level agreement on the need for labels and their minimum semantics, independent of their implementation.

To automate the processing of published and self-describing interfaces we require mechanisms for the accurate and rigorous specification of component interfaces in a manner that allows users and software to reason about their compatibility (or lack thereof).

Within the computer science community there has been considerable research on formal methods for the specification of interfaces. Although progress has been made, the methods that have been developed to date are limited and have not achieved widespread acceptance. However, perhaps progress could be made in a restricted sub-domain, e.g., if a few key NII interfaces were identified and a focused effort were made to develop techniques for their specification. In previous work [19] we have referred to these high leverage points as NII reference points.

**Conversion technology.** The components used during a VI transaction (or telephone conversation) are dynamically assembled. In some cases it will be possible to assemble a chain whose components have (pair-wise) compatible interfaces. However, it will often be the case that the examination of the component interface specification will identify mismatches between components that might otherwise be well-suited to the task at hand. In these cases, it may be possible to insert adapters into the chain. Much like electrical adapters used when traveling between countries, these adapters would bridge otherwise incompatible interfaces.

**Publication vs. standardization.** Standards are such a good thing that everyone would like to have their own.[8] In the case of mechanical connectors this is inappropriate - imagine the assortment of adapters you would have to carry if each town had a unique electrical connector. However, many digital components have soft, rather than mechanical, connectors. Furthermore, the marginal cost of software adapters (processing and storage) is declining rapidly. While it remains important to have well-specified published interfaces, there can be many of them.

## 5. Policy Implications

The virtualization of the nation's information infrastructure has several implications for regulation and the organization of business practices and ethics. The arguments we have developed should be equally applicable to the global information infrastructure (GII) identified in the Bangemann report [20]. However, we have focused on the domestic environment, especially with respect to policy issues. We would welcome work by others on the interpretation of these concepts within other national or international contexts.

Competitive markets are not free of all regulation - they simply require a different style of oversight than monopolies. A mosaic involving anti-trust, self-regulation and public commissions is likely to evolve. Accordingly, progress towards a **CGD** infrastructure does not depend so much on the elimination of regulation as its decoupling. The various parts of the infrastructure - supply, distribution, appliances, and brokerage - should be regulated separately. Some limited monopolies in information distribution may be necessary and these must be organized in a way that preserves the competitive structure of the information market as a whole. Finally, steps may be necessary to ensure the timely and accurate publication of interface specifications.

Much of the (proposed) U.S. legislation [2, 9] is consistent with our detailed prescriptions and we are not arguing against it. However, we would have preferred to see a proactive Communications Act that champions innovation and sets out a vision of the fundamental challenges and the means by which they will be addressed.

### 5.1. Decoupling the Regulation of Content and Carriage

When the infrastructure was not generic it was reasonable to couple the regulation of supply and distribution. However, if the infrastructure is generic, then coupling these two functions invites a monolithic and complex regulatory process that unnecessarily binds the entire range of suppliers and distributors into an interlocking structure.

Although we do not preclude the vertical bundling of services (see below), the bundling of regulation is another matter. It may present a barrier to entry for an innovative player who wants to provide a new service or deploy a new distribution technology. The present food supply and distribution industry presents an alternative structure that is reasonably successful. Different mechanisms and organizations oversee the safety of different types of food (e.g., baby food), the reliability of the food supply, the safety and reliability of the distribution system, the fairness of the various markets, and the safety of the appliances used.

### 5.2. Decoupling the Wireless Spectrum

Wireless has a special place as part of the network of networks - it can act as a "digital nursery." Its low fixed costs make wireless an ideal way to introduce new technologies on a small scale. Low startup cost is a critical innovative advantage; a successful service can move to a wired transport when demand grows enough to justify it.

We presently couple the allocation of spectrum to specific services and to specific modulation/coding technologies that implement the channels over which those services are

delivered. This leads to a *hard* view of spectrum in which each band is used to deliver a specific service with a specific technology. We envision a *soft spectrum* environment in which spectrum is fairly generic; that is, a service can be delivered over many different bands and technologies.[9] This is already happening in bands that are used with digital technology and the process should be accelerated so as to increase the pool of generic digitized spectrum. Although there may be public policy reasons for allocating capacity to certain purposes, those decisions should be decoupled from the choice of band and technology. This decoupling of policy and mechanism, through the deployment of technologies that can be configured to support a range of policies, is common practice in the design of computer systems and networks.

### 5.3. Decoupling Appliances

Many appliances will be generic and their regulation should no longer be bundled with the supply and/or distribution of information. Where monopolies exist, special care must be taken to exclude the appliances from the scope of the monopoly. The publication of suitable interfaces will allow others to develop and market adapters that bridge any gaps between appliances and distribution channels. In practice, we expect home users to purchase their own home information infrastructure (HII) and equip it with adapters that provide access to a range of distribution channels.

Our approach does not preclude the bundled marketing of appliances and distribution for the purpose of innovation - so long as it does not force an artificial coupling. The cellular telephony industry presents an interesting example. The industry bundles and discounts appliances in order to market their information and distribution services. However, the appliances are built within a competitive environment and are not tailored to a single provider's facilities. The packages are marketed through many different sales channels and there is ample room for competition and innovation. This is in sharp contrast to the settop box market where the appliances are ordered and marketed largely by the service providers. Although there has been some innovation in the settop market, the wholesale cost of the appliances seems very high when compared to other consumer devices of similar complexity.

### 5.4. The Distribution Mosaic

In Section 4.3.2 we discussed the organization of the distribution markets and observed that it would be difficult to stifle competition among the vendors that cater to large users and those that provide cross-connect services between pools of large and small users. However, the same logic does not extend to the small user pools, where monopoly players may gain control of whole types of distribution channels, such as the right to string coaxial cables in a neighborhood. Nonetheless we believe that competitive distribution is viable and offer two prescriptions to safeguard its realization and lower the barriers to innovation:

- Establish a mosaic of overlapping distribution channels.
- Restrict the scope of monopolies to specific assets.

Ideally, all of the digital distribution channels should be generic so that any channel could be used for any purpose. In practice, the distribution channels are not ideal; that is, they are not completely generic. Although it would be possible for digital information to flow over any of the distribution channels, some of the channels would be more appropriate for certain types of

information services (voice, video, Fax, etc.) than others.

No single channel will be suited to all of the information services that are offered. However, we envision a mosaic in which, for any given service, there is likely to be more than one channel to choose from. Similarly, any one channel will provide a range of services and compete for each of those services with some subset of the other channels.<sup>[10]</sup> In practice, each channel may have certain core strengths (e.g., killer applications) and compete with other channels at the fringes of its strengths.

Wireless distribution provides an important safety net within the distribution mosaic. In markets where the demand is not great enough to ensure competition and innovation within wired channels, the low start-up costs of wireless ensure the availability of an alternative channel. However, to fulfill this role, wireless must be a truly generic channel. Although its aggregate capacity may be limited, we should strive to maximize the range of services that can be carried. In Section 4.3.2 we highlighted the need to provide small users with instantaneous access to high bandwidth channels. The wireless spectrum provides a way to do this while maximizing the degree of resource sharing across pools of small users.

**Dealing with monopolies.** Although competition is our preferred approach, it may sometimes be appropriate to accept limited monopolies within the NII. However, we should establish stringent tests for why monopolies are required and what their scope should be.

Granting a monopoly encourages deployment of today's technology by granting the investor a degree of protection from new technologies. We should be aware that in return for the investment we are, in effect, providing the investors with insurance against innovation [22-24]. If monopolies are necessary to the development of a particular type of distribution channel, then we offer the following prescriptions for their regulation:

- They should be of minimum scope; that is, they should cover only as much of the distribution system as necessary.
- Franchises should be of limited duration and not eligible for renewal.
- The regulation of services, distribution, and appliances should be decoupled.
- Open interconnections should be required at both ends of the monopoly channel, so that all suppliers can arrange access, and any customer can buy equipment (such as a settop box) from any reputable source and connect it to the channel.

**Vertical integration and bundling.** We have presented arguments supporting the vertical decoupling of the information industries. In the absence of artificial barriers, we believe that this decoupling will occur naturally and that, subject to the prescriptions above, vertical integration should not be prohibited. Some [25] argue that it is difficult to dismantle vertically integrated organizations. However, we note that the cable companies are presently partitioning their assets into different corporate entities - a move which may mark the beginning of this process.

The historic advantage of vertical integration has been lowered transaction costs; if a business is tightly coupled between the supply, distribution, and consumer appliance segments, then the transactions between those segments can be made cheap and efficient. However, as we have shown, digital technology reduces the cost of dynamically assembled supply chains. Provided

the degree of human intervention associated with each transaction is declining. As the transaction costs go down, the units of transaction can be smaller and more frequent. Thus we would not expect vertical bundling to confer an advantage.

## 5.5. Publication of Interfaces

Many consider standards to be of great importance to the development of the NII. Although standards for mechanical interfaces will continue to be important, there will be far too many soft interfaces to ever consider standardizing them all. Innovation will be enabled more effectively through the timely publication and dissemination of accurate specifications of these interfaces.

However, access to a specification is not sufficient if one is precluded from building an adapter by intellectual property rights (IPR) that cannot be licensed in a convenient and cost effective manner. Many researchers are dealing with the overall IPR question. We would like to draw their attention to the narrower question of component interfaces and the question of building adapters that support interoperation with them.

The first question that should be addressed is whether it is appropriate to grant protection on interfaces and, if so, what is the appropriate vehicle (e.g., copyright, patent, trade secret). Although we may have personal views on the matter, we have not identified a policy reason to refuse such protection, provided that it does not apply to interfaces to monopoly assets, and that there is some mechanism through which competitors can be readily licensed to build adapters for software licensing [26] might be applicable.

It is also possible that the dominant business ethic will come to favor the public and free distribution of interface specifications.[11] In most cases, the vendor of a product benefits from having a good specification of its interfaces. The question is whether or not they publish that specification and do so in a manner that engenders confidence in its completeness and accuracy. Microsoft's Rich Text Format (RTF) provides an interesting example concerning the publication of interface specifications. Microsoft relies on the RTF specification for its own purposes (e.g., to support interoperation across its own product line). RTF also allows Microsoft's competitors to produce adapters that support interoperation with its products. In the case of RTF, Microsoft determined that publishing the specification would encourage others to market value-added products that would increase the market for its own products.

## 6. Conclusions

In this paper we have described our vision of a Virtual Infrastructure (VI) that is based on the fundamental properties of digital information. We have presented a taxonomy for describing alternative infrastructure scenarios and shown how the key properties of digital information favor a competitive, generic and decoupled (CGD) infrastructure, and how such an infrastructure favors innovation.

However, we have also shown that, despite the current emphasis on competition, the present *convergence* activities could inadvertently establish artificial barriers that would lead us back to a regulated monopoly - one that is generic and thus far more pervasive than those of the past. Ultimately, we believe that the digital properties will destabilize such a monopoly, but only



after a lengthy interval. It would be preferable to avoid the monopoly state entirely and proceed directly to a VI. Realizing this vision will require a synthesis of technical and policy efforts and Sections 4 and 5 represent our first pass at enumerating the challenges that lie ahead.

Others have identified some of the issues that are raised in this paper. However, we believe that there is novelty in our taxonomy and in the chain of reasoning through which we link CGD to the underlying digital properties and to the VI and its means of realization. The underlying drivers, which are tied to the technology curve are:

- The declining cost of digital conversion. Conversion enables heterogeneity, which in turn enables competition and innovation.
- The increased capability of digital devices to support the rapid configuration and allocation of resources. This driver is both a result of and an enabler of software. The net effect is a drive towards a more dynamic and virtualized infrastructure.

In conclusion, we find that competition is important and intertwined with the advance of technology. However, it is the rapid digitization and virtualization of the infrastructure that is the major development driving the process. Accordingly, we consider it appropriate that the NII vision be rooted in and compatible with the fundamental properties of digital information and devices.

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