The Economic Geography of the Internet's Infrastructure*

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Abstract: The Internet is perhaps the defining technology of the emerging twenty-first century. This article examines the infrastructure that comprises the "network of networks" and the spatial patterns that have emerged in the Internet's short existence. In its brief history, the Internet has manifested a tentative relationship with the urban hierarchy. This relationship is tracked over a four-year period (1997 to 2000), during which firms made massive investments in new fiber-optic lines and upgrades. A global bias of Internet backbone networks toward world cities is evident, and it is tempered only slightly by a set of urban areas that serve as interconnection points between backbone networks. Interconnection is both critical to the functioning of the Internet and the source of its greatest complications.

Key words: Internet, networks, telecommunications, urban hierarchy, world cities.

The Internet is arguably the most significant technology of the intermillennial era, the leading technology of the fifth Kondratiev wave (Hall 1998). It fills this role, in part, because it is a general-purpose technology (GPT)—one of a small number of drastic innovations that creates innovational complementarities that increase productivity in a downstream sector (Helpman 1998). The Internet clearly qualifies as a "key" technology, characterized by the potential for pervasive use in a wide range of sectors and by its technological dynamism, and as an "enabling technology," opening up new opportunities rather than final solutions (Bresnahan and Trajtenberg 1995). GPTs have a great impact because of their scope for improvement, wide variety of users, wide range of uses, and strong technological complementarities. Historically, writing, printing, and electricity were GPTs; recent examples, in addition to the Internet, include lasers, the factory system, mass production, and flexible manufacturing (Lipsey, Bekar, and Carlaw 1998).

The newness of the Internet has masked the fact that the Internet continues several long-standing characteristics of communications technologies (see the review in Malecki 2001). Four of these persistent trends are the most important for the present article. First, large firms, particularly banks, which were central to the development of high-speed data transfer technologies, had earlier greatly influenced the telegraph and the evolution of all subsequent communications technologies. This is, in part, a result of a second feature common to all telecommunications technologies since the telegraph: that moving intangible, invisible information is not the same as the transportation of goods. It is much easier and can be highly profitable to transmit invisible commodities (Hillis 1998). Financial tallies that represent money have been among

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the easiest items to send across the ether, and all of the largest categories of online or e-commerce to date are intangibles: travel and ticketing services, software, entertainment (including gambling, music, online games, and pornography), and financial services (Wyckoff and Colecchia 1999).

A third feature common to all telecommunications technologies is that telecommunications is at "the extreme end of the systemness spectrum" because of a primary distinctive feature: it functions as a network with simultaneous utilization by many users (Rosenberg 1994, 208). A related concept is that of network economies, which suggests that a network (and any node on a network) is more valuable the greater the number of users (or other nodes) on the network (Katz and Shapiro 1994; Lehr 2001).

The fourth and final way in which the Internet reiterates the past is the centrality of "private roads" or private telecommunications networks (Gillespie and Robins 1989). The use of leased fiber-optic lines by global firms for their internal networks merely continued a trend that began in the 1870s, when U.S. banking firms assembled coast-to-coast private telephone networks and, with European bankers, were among the backers of the transatlantic cables (Gabel 1996; Hugill 1999). The early private networks were created to establish more reliable service, not only for banks but also for newspapers to transmit telephotographs and facsimiles. Private networks of leased lines remain the core of the Internet and collectively are "far larger" than the public Internet (Coffman and Odlyzko 1998; Paltridge 1999). The result is that the Internet is a largely unregulated system into which corporate networks have hooked (Schiller 1999). The unregulated nature of the Internet has received the unofficial status of policy within the U.S. Federal Communications Commission (FCC) (Oxman 1999). As deregulation and privatization diminish the significance of national telecommunications monopolies, "it is possible that eventually the only communication infrastructure will be a set of interfaces among myriad private networks" (Crandall 1997, 168).

The remainder of this article proceeds, first, by setting research on the Internet into the context of conventions within economic geography. The market or industrial structure of the Internet is an outcome of the firms that have invested in "backbone" networks and smaller networks that constitute it. The backbone networks define the superstructure or outline of the Internet's infrastructure and, consequently, its close relationship with the urban system. The article then focuses on interfirm linkages as they are manifested through interconnection of the many networks of the Internet. The spatial agglomeration of linkages and linkage sites is set in the context of the urban hierarchy of world cities. Taken together, the nodes and links of the network of networks define the geography, although not the content, of the space within which digital flows take place.

Economic Geography and the Internet

A great deal of the research on the Internet has stemmed from research paths outside mainstream economic geography. What is the mainstream? Scott (2000) suggested that "flows and interactions through space" were among the preoccupations of spatial analysts—both economic geographers and regional scientists—until perhaps the early 1970s, when interest waned and shifted toward political economy and local and regional economies. Other topics, such as localized production systems, institutions and local labor markets, and dynamic learning and innovation processes, were among the lines of investigation, and the term *networks* began to take on a rather distinct meaning from that of *transportation* and *communication*. To some degree, a parallel focus on globalization, including transnational corporations and the international division of labor, has always involved global flows at least implicitly. Indeed, communications technologies were among the enabling factors behind the creation of global corporations, along with the growth of international governance institutions, such as the United Nations, the International Monetary Fund, and the World Bank (Dicken 1998; Michie and Smith 1995; Sassen 2000). Likewise, any probing of the geography of money and finance has immediately recognized the telecommunication networks on which the global financial system depends (e.g., Leyshon 1996; Warf 1995).

The Geography of Cyberspace

As a phenomenon of the 1990s, then, the Internet as a topic of research has attracted the attention of economic geographers and other social scientists. A large cluster of research on the Internet has sprung from those who have been concerned with social phenomena and for whom *cyberspace* represents a separate space in which people live and operate (Hillis 1999; Kitchin 1998). Cyberspace represents a "middle landscape" that allows individuals to exercise their impulses for both separation and connectedness (Healy 1996). Cyberspace, the interactivity between remote computers (and from nodes to nets) for real communication, not just data transfer, is not necessarily imagined. As Kwan (2001, 23) pointed out, there is no sense of place or of distance or direction because "there is no geographical landmark or physical movement in cyberspace for telling either distance or orientation." In addition, people can perceive only a small part of the World Wide Web at one time before disorientation and cognitive overload set in.

Batty (1997) suggested that cyberspace is only one of four spaces of *virtual geography* created by computers and communications. The other three spaces are *place/space* (traditional geographic abstractions of place, such as cities as nodes); *cspace,* or computer space (i.e., inside computers and their networks, including geographic information systems); and *cyberplace,* or the impact of the infrastructure of cyberspace on the infrastructure of traditional place. It is this last space, cyberplace, that is most easily subsumed within economic geography. It consists of all the wires that make up the networks that are embedded into structures; these wires are only partially charted and, indeed, are difficult to chart. All networks, including wireless networks, have a built infrastructure that relies on antennas and connection with conventional telephone switches. In effect, cyberspace depends on the "real world spatial fixity" found in cyberplaces (Kitchin 1998). Generally, the many geographies of cyberspace and other virtual spaces are only beginning to be understood (Adams 1997; Crang 2000; Dodge and Kitchin 2000; Donert 2000; Kitchin 1998). An important point, as Warf (2001) noted, is that the analysis of cyberspace is only part of the broader debate about the nature of representation and the discursive construction of space—both of which are linked to power relations.

A multidimensional framework, therefore, is necessary to comprehend the effects not only of the Internet but of related economic and technological developments. Ohmae (2000) also saw various spaces or dimensions in what he described as a new *invisible continent* in which the global economy takes place. A *visible dimension* contains economic dimensions of the old world, such as net present value (NPV), local commerce for delivery, and bakeries baking cakes—sometimes described as the "mortar" dimension of the "clicks-and-mortar" world. Although they are largely invisible, economic transactions remain rooted in a tangible world. A *borderless dimension* is illustrated by electronic communication that transcends national borders and perhaps most by the cross-border migration of capital. A *cyber dimension* is represented by the computer and communications technologies that have changed the consumer, producer, and civic environments in irrevocable ways. The cyber dimension includes the Internet as well as call centers and mobile phones. A *dimension of high multiples* is based on a set of imaginative assumptions—whether in the form of speculators' leverage or the price/equity (P/E) ratios of equity markets. Ohmae's final dimension takes into account the significance of perceptions, seen recently in the rapidly changing fortunes of dot.com firms, which has reflected both the power of perceptions and the instability of those perceptions.

The combination of technological and economic trends also merges within e-commerce. In this context, several *layers* of infrastructure can be identified (Center for Research in Electronic Commerce 2002):

Layer 1: Internet Infrastructure—telecommunications companies, Internet service providers (ISPs), Internet backbone carriers, "last mile" access companies and manufacturers of end-user networking equipment.
Layer 2: Internet Applications Infrastructure—software necessary to facilitate web transactions and transaction intermediaries; consultants and service companies that design, build and maintain web sites, from portals to full e-commerce sites.
Layer 3: Internet Intermediaries—web-based businesses that generate revenues through advertising, membership subscription fees, and commissions. Some layer three companies are purely web content providers; others are market makers or market intermediaries.
Layer 4: Internet Commerce—companies that are conducting web-based commerce transactions.

In a somewhat different organization by Zwass (1999), seven levels of e-commerce are organized into three meta levels: infrastructure, enabling services, and the products and services themselves.

It is clear from these varied attempts to categorize and comprehend the Internet that it is forming a new economic space, with a great deal of free content provided by for-profit enterprises, as businesses attempt to "enmesh the user" by providing multiple reasons for the users' continued patronage; Amazon and Yahoo are prominent examples (Kenney and Curry 2001). The Internet confronts business with four unique characteristics: ubiquity, interactivity, speed, and intelligence. Under these circumstances, it should not be surprising that more than one business model applies. Many activities, such as complex coordination tasks and intellectual activities, require face-to-face communication and therefore agglomeration, whereas other activities that focus on physical distribution can be more dispersed (Goodchild 2001; Leamer and Storper 2001). "The costs of sending requests via the Internet, and to receive goods via express delivery services are both largely independent of distance, so there are no longer any incentives for entrepreneurs to locate close to consumers" (Goodchild 2001, 69). In addition, strong scale economies are associated with e-commerce operations like Amazon.com.

Infrastructure and the Space of Flows

What is evident from these various perspectives of the Internet as a multidimensional phenomenon is the persistent significance of infrastructure, whether measured as networks, facilities, equipment, or other fixed investments that facilitate electronic interaction. While some of the infrastructure has been in place for decades in the public switched telephone network (PSTN), it was the emergence of data traffic (including faxes and other nonvoice communication) that prompted investment in fiber optics, which facilitate faster transmission not meaningful for voice communication. The advent of the Internet, corporate intranets, e-commerce, and consumer web sites has compelled networks to respond to the significance of data communication, which is growing far faster than voice traffic (Hulfactor and Klessig 2000; Wellenius, Primo Braga, and Qiang 2000). Data traffic demands high-speed (high bandwidth) links to transmit video (especially) at normal speeds.[1] Indeed, the digitization of several

[1] *Bandwidth* is the term commonly used to designate transmission speed, measured in bits per second. A simple "rule of thumb is that good video requires about a thousand times as much bandwidth as speech. A picture is truly worth a thousand words" (Mitchell 1995, 180, note 28). *Broadband* generally refers to transmission speeds above 64kbps, the base normal speed of a voice call (Huston 1999a, 160–71). Higher bandwidths generally are made possible by multiplexing the baseline.

intangibles, such as music and video, has accounted for much of the growth in data traffic. Exactly how much traffic is not known; Coffman and Odlyzko (2002) suggested that we simply do not have comprehensive data on flows, yet best estimates confirm that traffic is probably doubling each year. Without better measurement and data collection, we cannot really assess the different kinds of information activities, their agglomeration, or their impact (Lamberton 1997).

Castells's (1989; 2000, 442) term, the *space of flows,* attempts to capture the new spatial form, "the material organization of time-sharing social practices that work through flows." The global economy is increasingly constituted of flows that connect, in particular, large metropolitan nodes, primarily through producer services, including financial services (Graham and Marvin 1996; Sassen 2000). At the same time, there are "black holes" of marginality with respect to advanced services, including the districts housing low-wage workers that support the digitized economy. Graham and Marvin (2001) referred to the new urban pattern as an "archipelago economy," comprised of interconnected networked enclaves ("premium networked spaces") and unconnected "network ghettoes" within the same urban areas. The "new geography" is a result of the fact that only some places are successful in attracting mobile firms and professionals (Kotkin 2000).

Castells (2000, 442–45) distinguished among three dimensions or layers within the space of flows. The first layer, the material support for the space of flows, is constituted by a circuit of electronic exchanges. It is largely the technological infrastructure of telecommunications networks, akin to Batty's (1997) cyberplace. The second layer is made up of its nodes and hubs, which are hierarchically organized and have well-defined specializations in certain social, cultural, physical, or functional areas. That is, not all global cities are alike; each has its own "competitive advantage." The third layer refers to the spatial organization of the dominant, managerial elites, which are increasingly isolated in premium infrastructure spaces, whether in California or Cairo (Castells 2000, 447; Graham and Marvin 2001). Although the popularization of the Internet has spread its use well beyond the elites to which Castells refers, there remains what has been termed a "digital divide" between users and nonusers of the Internet (National Telecommunications and Information Administration 2000; Warf 2001).

The space of flows is seen most clearly within the corporate networks of multinational or transnational firms, which have been prominent users of telecommunications networks as enablers of their global reach (Dicken 1998). Transnationals rely on a "double network" that is comprised of both an *internal network* and a set of *external networks* (Zanfei 2000). Both types of networks use communication links as well as face-to-face contact (Moulaert and Gallouj 1993). Early work by Goddard and Pye (1977) on communication within large firms, extended to the dual-locational Asea Brown Boveri Ltd. (ABB) by Lorentzon (1995), clearly showed that electronic communication complements and reinforces face-to-face contacts (Gaspar and Glaeser 1998; Moss 1998). Indeed, business travel shows no sign of decline despite the massive growth of data traffic. The persistence of agglomeration within cities is due to the need for "handshakes" and tacit exchanges of knowledge that can take place only face to face, in contrast to "conversations" that can be exchanged electronically (Leamer and Storper 2001). Although data traffic continues to grow, the fiber-optic "pipes" are not full all the time; in fact, the use of corporate networks is not particularly high. Odlyzko (2000) suggested that the average use of corporate networks over a full week is around 20 percent, with occasional spikes of demand, a figure that matches the usage of three redundant networks by one firm reported by Roberts-Witt (2000).

Even though data traffic is perceived as "free" to many users and it is easy to retrieve information across long distances almost instantaneously (depending, in particular, on the last-mile link to one's computer), distance is not "dead." Even Cairncross (2001), the title of whose book is routinely cited in this regard, recognized that the story is more subtle: "The death of distance loosens the grip of geography. It does not destroy it" (Cairncross 2001, 5). The falling cost of communication has not been equal everywhere. Large cities continue to dominate both in network connections and in the agglomeration of face-to-face (or handshake) activities for which "the tyranny of proximity" has replaced the tyranny of distance (Duranton 1999).

The concept of world cities, or global cities, represents a second body of theory that is particularly useful for understanding the economic geography of the Internet on the global scale (Friedmann and Wolff 1982; Knox and Taylor 1995). The Globalization and World Cities (GaWC) Study Group at Loughborough University has operationalized Castells's space-of-flows concept to the global city system, defining a "meta geography" based on relational links (Beaverstock, Smith, and Taylor 2000; Taylor 1999). If one demarcates *alpha*, *beta*, and *gamma* world cities as three meaningful tiers, the *alpha* tier includes the usual urban triumvirate (London, New York, and Tokyo) but also Paris. At a slightly lower level of "world cityness" are Chicago, Frankfurt, Hong Kong, Los Angeles, Milan, and Singapore. In examinations of the producer service firms that operate in world cities, most cities group into regional or interregional clusters; only London and New York form their own distinctive "global city" dimension (Taylor and Walker 2001).

Following producer service firms to the cities in which they operate are the backbone networks that together form the global structure of the Internet. The urban hierarchy defined by Internet backbones varies from that identified by the GaWC research, as the next section shows.

The Geography of Internet Backbones

The original Internet network was little more than a back-of-the-envelope sketch of connections among four university nodes: the University of California at Santa Barbara, UCLA, the Stanford Research Institute, and the University of Utah in Salt Lake City (Abbate 1999). As computing and communications technology converged, private networks grew to serve corporate clients (Langdale 1989). It is the new telecommunications carriers, as well as the old telecom monopolies—many of which have become global players through acquisitions, mergers, consortia, and other arrangements—whose individual networks make up the present Internet. However, deregulation or liberalization are perhaps as significant as technology in forming the structure of the Internet (Finnie 1998; Graham 1999). Paltridge (2000) made the case that access prices—lower in competitive markets—largely determine Internet use. The Organization for Economic Cooperation and Development (OECD 2001), for example, has instituted a regularly updated local Internet price comparison.

The competitive environment means that universal service, a mantra of the regulated era of voice communications, has been replaced by "cherry picking" and opportunistic behavior by the various backbone networks as they attempt to tap the demand in the world's largest cities. Within those cities, it is the central business districts and their potential clients—office tower-dwelling producer service firms—that attract the most investment, reversing decades of unrelenting suburbanization (Graham 1999). WorldCom (and its many subsidiaries) represents the new telecom strategy: to be a global fiber provider in an archipelago of wired cities, offering "route diversity" and largely bypassing the PSTNs and participating in consortia for investment in new underseas cables (Graham 1999). Although there is no single map of the Internet, Dodge (2002) continues to compile what is known about it, including several of the backbone networks and the local mesh of fiber-optic networks in several cities.

The Internet and World Cities

In places where the deregulation of telecommunications has been more thorough, a larger number of new firms have emerged to compete with former monopolies. These new carriers must interconnect with both existing carriers and with each other to provide global service to their corporate customers. "The Internet cannot bypass mega-cities: it depends on the telecommunications and on the telecommunicators' located in those centers" (Castells 2000, 440; Sassen 2000). Finnie (1998) presented pricing, choice, and availability in 25 large cities in 1998; 11 cities had only one or two fiber-optic networks. At the other end of the spectrum, New York had nine networks; London, Los Angeles, and San Francisco had six networks; and Atlanta, Chicago, and Kuala Lumpur had five. Greater competition results in both greater choice and lower telecommunications prices.

Table 1 shows the connectivity of European cities on 20 networks that serve the continent. Amsterdam, merely a *gamma* world city in the GaWC metageography, is second behind London and ahead of Paris, Frankfurt, and Hamburg. London is the only city connected by all 20 European networks. Thus, there are elements of a stable hierarchy of world cities and, at the same time, signs that "new network cities" have achieved advantages in the age of the Internet (Graham and Marvin 1996; Townsend 2001). Globally, Press (2000, Fig. 7) illustrated the central position of the United States, Europe, and, to a lesser degree, Australia on the network comprised of 48 of these backbone networks. The U.S.-centric nature of the Internet, prominent in the late 1990s (Cukier 1999), is slowly diminishing. Over 20 networks are being built in Europe, for example, by telecommunications providers whose customers demand seamless global communications.

A large number of firms provide long-haul transmission, but the market is dominated by three firms, WorldCom, Sprint, and Cable & Wireless, which together accounted for perhaps 55 percent of the Internet market in 2000 and still dominate it today (TeleGeography 2000c, 57; TeleGeography 2001, 139–46). These firms and their

Table 1

Connectivity of Cities in Europe on 20 Networks

City	Number of Networks
London	20
Amsterdam	19
Frankfurt, Hamburg, Paris	18
Berlin, Brussels, Düsseldorf, Milan, Munich, Zurich	17
Geneva, Madrid, Stockholm	15
Marseilles, Oslo	14
Barcelona, Copenhagen, Lyon, Strasbourg, Stuttgart	13
Vienna	12
Bordeaux, Cologne	11
Bilbao, Dublin	10
Rotterdam, Valencia	9
Antwerp, Dresden, Gothenburg, Hannover, Leipzig, Nuremberg, Toulouse, Turin	8
Basel, Helsinki, Prague	7
Manchester, Rome	6
Birmingham, Bremen, Budapest, Edinburgh, Lille, Warsaw	5
Bristol, Leeds, Malmö, Moscow	4
Belfast, Bern, Bonn, Bratislava, Lisbon, Porto, Tallinn	3

Source: Calculated from the City Connectivity Matrix in TeleGeography (2000a, 132–34).

competitors have invested heavily to install new fiber-optic cables and in new technologies that provide greater bandwidth capacity. A great deal of new fiber-optic capacity has been installed throughout the world, much of it "dark" fiber in anticipation of future demand. Dark fiber is fiber-optic cable that has not yet been "lit" by the optoelectronic equipment that facilitates the transmission of data. Indeed, several firms in the electricity, pipeline, and railroad sectors have installed such fiber along their rights-of-way. Technological change has also permitted massive increases in bandwidth, the speed at which data can be transmitted through the cable.

Growth in backbone capacity is among the most prominent trends in Internet development (National Research Council 2001). Table 2 illustrates the massive investment in Internet backbone capacity that occurred between 1998 and 2000 in the United States. In early 1998, all 38 backbone networks claimed bandwidth of DS-3, or 45 megabits per second (Mbps), on their backbones, and only 13 of them offered any higher bandwidth, such as OC-3 (155 Mbps), OC-12 (622 Mbps), and OC-48 (2,488 Mbps or 2.488 gigabits per second (Gbps)). Higher bandwidth was implemented rapidly over the next two years. In mid-2000, only 59 percent of U.S. backbones still operated any links at the slowest (DS-3) bandwidth; fully 63 percent (26 networks) had installed capacity of 622 Mpbs (OC-12) or faster, and 41 percent (17 networks) had bandwidths of 2,488 Mbps or faster. Such bandwidths easily overwhelm networks of the slower capacity: a single OC-48 cable has the same bandwidth as 55 of the older DS-3 capacity.

International routes have concentrated on the *alpha* world cities, to some degree, but it is clear from Table 3 that the set of best-connected cities is mainly in Europe and that redundant, high-capacity routes are fewer to Asian cities: Tokyo (ranked 15), Hong Kong (ranked 28), and Singapore (ranked 33). Chicago (ranked 14), Milan (ranked 16) and Los Angeles (ranked 25) also fall well short of their standing in the GaWC meta-geography, which focuses on the office locations of producer service firms and implicitly incorporates travel and market factors, as well as Internet traffic. However, Europe appears to form a coherent *panregion* (Taylor 2001) and a growing counterweight to the "bandwidth colonialism" by the United States that appeared to prevail only two years ago (Cukier 1999).

Tracking the Growth of the Internet

Several recent analyses of Internet backbones have ranked U.S. cities or metropolitan areas according to measures of their Internet connectivity (Malecki and Gorman

Table 2

Bandwidth on Backbone Networks of U.S. Backbone Providers

Bandwidth on Network Links	1998 (38 networks)	2000 (41 networks)
DS-3 (45 Mbps)	38 (100%)	24 (59%)
OC-3 (155 Mbps)	10 (26%)	26 (63%)
OC-12 (622 Mbps)	5 (13%)	15 (37%)
OC-48 (2,488 Mbps)	2 (5%)	12 (29%)
OC-96 (4,976 Mbps)	0	1 (2%)
OC-192 (10,000 Mbps or 1 Gbps)	0	4 (10%)
Number of networks with bandwidth 622 Mbps (OC-12) or higher	7 (18%)	26 (63%)
Number of networks with bandwidth 2,488 Mbps (OC-48) or higher	2 (5%)	17 (41%)

Source: Compiled from data in Boardwatch (1998 and 2000).

Table 3

Top International Internet Hub Cities, 2000

Rank	City	International Internet Bandwidth (Mbps) (Omits Internal Country Routes)
1	London	86,590
2	Amsterdam	68,302
3	Paris	62,197
4	New York	61,071
5	Frankfurt	52,332
6	Stockholm	18,652
7	Brussels	18,631
8	Geneva	17,849
9	Toronto	16,399
10	Düsseldorf	15,863

Source: Adapted from TeleGeography (2000c, 107).

2001; Moss and Townsend 2000; Wheeler and O'Kelly 1999). Several different measures are used, with slightly different results, but San Francisco; Washington, D.C.; and Dallas generally outrank the much larger areas of New York and Los Angeles, suggesting that Internet accessibility is responding to a demand that is beyond, or different from, that measured by population alone. This finding is especially strong when bandwidth-weighted links are analyzed (Malecki and Gorman 2001; Moss and Townsend 2000).

Comparisons and analyses over time have been rare in the context of the Internet's recent and sudden growth. Gorman and Malecki (2000) compared several Internet backbones in the United States, focusing on the change for Cable & Wireless after it acquired the MCI backbone network from WorldCom, a divestiture required for the FCC's approval of WorldCom's acquisition of MCI. Their analysis showed that what appears to be a single network was, in fact, dramatically different: Cable & Wireless was able to serve new cities, and much more efficiently. Now, the Cable & Wireless network in the United States is one of the best-connected networks, even though its core network serves only a small number of large metropolitan areas (http://www.cwusa.net/Internet_backbone.htm).

Moss and Townsend (2000) presented one of the few analyses of Internet *growth*, comparing the intermetropolitan Internet backbone capacity in the United States in 1997 and 1999. The 1997 data included 29 networks, and there were 39 by the spring of 1999. Moss and Townsend (2000, 41) found that a "core group of seven metropolitan areas (San Francisco/San Jose, Washington, D.C., Chicago, New York, Dallas, Los Angeles, and Atlanta) had maintained their dominance as the central nodes of the Internet in the United States." They also found that a group of metropolitan areas in the central part of the country had become "hubs for new, large network links" (p. 41). In addition, they found that the United States's global cities—New York, Chicago, and Los Angeles—were relatively weak in backbone links. Similarly, Boston and Seattle, well known for their technology-based firms, ranked below Atlanta and Dallas—largely, they maintained, because of the geographically central locations of the latter.

Table 4 builds on the data compiled both by Moss and Townsend (2000) and Malecki and Gorman (2001). The 1998 data in the latter came from the compilation of links on 33 networks compiled by the Cooperative Association for Internet Data Analysis (CAIDA). The 1997, 1998, and 1999 compilations were based largely on the data

Table 4

Total Internet Bandwidth Connecting U.S. Metropolitan Areas, 1997–2000

Rank	Metropolitan Area	Population 1999	Total Bandwidth on Internet Backbones (to or from metropolitan area), in Mbps			
			1997	1998	1999	2000
1	New York	20,196,649	6,766	9,543	22,232	234,258
2	Chicago	8,885,919	7,663	14,809	23,340	221,738
3	Washington, D.C.	7,359,044	7,826	14,174	28,370	208,159
4	San Francisco	6,873,645	7,506	14,924	25,297	201,772
5	Dallas	4,909,523	5,646	10,985	25,343	183,571
6	Atlanta	3,857,097	5,196	5,426	23,861	149,200
7	Los Angeles	16,036,587	5,056	9,397	14,868	140,649
8	Seattle	3,465,760	1,972	5,409	7,288	109,510
9	Denver	2,417,908	2,901	5,942	8,674	97,545
10	Kansas City	1,755,899	1,080	2,715	13,525	89,292
11	Salt Lake City	1,275,076		495	9,867	87,624
12	Houston	4,493,741	1,890	3,061	11,522	80,483
13	Boston	5,667,225	1,325	2,785	8,001	75,044
14	Philadelphia	5,999,034	1,610	5,045		74,167
15	St. Louis	2,569,029	1,350	1,800	10,342	69,031
16	Portland	2,180,996		765		68,174
17	Cleveland	2,910,616	1,080	3,461	6,201	61,671
18	Detroit	5,469,312	900	1,309		53,262
19	Phoenix	3,013,696	1,890	2,565	6,701	45,868
20	Orlando	1,535,004		990		45,528
21	Las Vegas	1,381,086		585	4,791	42,414
22	Miami	3,711,102	1,567	1,575		42,138
23	San Diego	2,820,844	870	1,495		42,062
24	Sacramento	1,741,002		675		40,702
25	Indianapolis	1,536,665		315	9,307	39,484
26	Charlotte	1,417,217		360	5,191	35,441
27	Tulsa	786,117				34,906
28	Austin	1,146,050		1,522		32,884
29	New Orleans	1,305,479		720		32,777
30	Tampa	2,278,169		810		30,310
31	Minneapolis	2,872,109		1,570		29,734
32	Pittsburgh	2,331,336		2,565		25,178

Source: 1997 and 1999: Moss and Townsend (2000); 1998: data compiled by Sean Gorman from CAIDA (Winter 1998); 2000: data compiled from *Boardwatch Directory of Internet Service Providers* 12th ed. (2000) and firm web sites. Urban areas are MSAs or CMSAs.

from the annual *Boardwatch Directory of Internet Service Providers* and included the network for MCI, which, at that time, refused to provide enough data to be included in the *Boardwatch* directory. This article adds a compilation of data for the links of 41 networks in mid-2000. The group of seven core metropolitan areas from Moss and Townsend (2000) remains, but may be seen to have collapsed in 2000 to a group of five—such is the gap between Dallas and Atlanta. There are no other obvious breaks in the numbers for 2000.

The compiled bandwidth on the 105 largest intermetropolitan links (all those with at least 5,000 Mbps in total bandwidth) is shown in Figure 1. Three groups of links are evident: (1) long-haul links that connect the largest cities, including the group of seven; (2) a large number of shorter-distance

Figure 1. Largest combined intermetropolitan links on 41 Internet backbone networks, 2000.

links that connect cities within the regions surrounding the major Internet hubs; and (3) a number of alternative paths that connect the major hubs via redundant paths, providing alternative routes for data flows. The 105 routes in Figure 1 represent less than 9.6 percent of the 1,100 fiber-optic lines linking U.S. cities, but they account for 34.4 percent of the total bandwidth linking 152 metropolitan statistical areas (MSAs). The largest interurban links are relatively short distance and have attracted a large proportion of the 41 firms that operate backbones to serve cities such as New York–Washington, D.C. (55,059 Mbps—25 firms); Los Angeles–San Francisco (44,636 Mbps—30 firms); and Boston–New York (44,281 Mbps—23 firms). It is these high-traffic routes that have attracted investment by multiple backbone providers. On the longer-haul routes, such as San Francisco–Washington, D.C. (23,906 Mbps—16 firms) and Chicago–Seattle (11,440 Mbps—11 firms), there tends to be less competition. As with airline connections, there are few "nonstop" long-distance routes; most traffic travels through intermediate hubs. The Los Angeles–New York route had only 4 of the 41 backbone networks in 2000, none of them high capacity, and their bandwidth totaled only 825 Mbps, far smaller than the smallest links (5,000 Mbps) shown in Figure 1. Data traffic between New York and Los Angeles travels easily, for example, through Washington, D.C.; Atlanta; and Dallas or through Chicago and San Francisco—all major links evident in Figure 1.

The bandwidth figures reported here are for backbone networks, which do not account for all the Internet transmission capacity in the United States or any other country. Several categories are excluded: (1) The networks of the regional Bell Operating Companies and the part of Verizon's former GTE local service areas, which connect the national backbones to local users in their service area communities. (2) Internet2 links that connect most research universities to the high-speed Abilene backbone. (3) Bandwidth that belonged to carriers' carriers, such as the pipeline companies Enron and Williams Communications, which built national networks, and subsidiaries of several utilities and railroads, which have built regional networks. These firms primarily lease bandwidth to other firms, and it is impossible to know how much of the networks of the backbone providers here is included and how much is excluded. (4) Local networks, often operated by ISPs that are also telephone providers, which may serve as the primary link to the Internet for colleges and universities and other large customers. (5) Metropolitan area networks that link sites within metropolitan areas.

All of these categories add considerable, but unknown amounts of, bandwidth to individual locations. Many providers make available only scanty data on their networks. Some provide a great deal of detail; others very little. In several cases, the regional and local networks function by leasing and trading bandwidth with other, often national, carriers whose networks are included in the totals reported in this article. The advantage of the *Boardwatch* data used here is the consistent format, including details on the bandwidth on each network link.

The Influence of Urban Area Population

Table 5 compares the top ten urban regions in bandwidth for each of the four years. What is most striking is that New York and Chicago rose to the top of the list in bandwidth in 2000. New York, the most populous metropolitan region in the United States, had ranked no higher than fourth in any of the three preceding years and, indeed, had fallen to sixth in 1999 in Moss and Townsend's analysis. What is also significant is that the "core group of seven" urban regions remained in effect. The stability of the top group, despite internal shuffling, suggests that "the new information and communication technologies *per se* do not make local and regional milieux dynamic but, rather, . . . more dynamic milieux are better able to use new technologies to their advantage than are less dynamic ones" (Gilbert and Villeneuve 1999, 115).

To what degree does population account for the installation of backbone bandwidth? Table 6 illustrates the role of urban area population alone on the data in Table 4. Notwithstanding the small number of cities analyzed, particularly for 1997 and 1999, urban area population explains from one-third to three-fifths of the variance across the four years (in log-log specifications). The best fit was for 1998 when, as Table 4 indicates, a large number of small to midsize urban areas, such as Portland (Oregon), Orlando, Indianapolis, Las Vegas, and Charlotte, had relatively small amounts

Table 5

Top Ten Metropolitan Areas in Total Bandwidth on Internet Backbones Serving Them

1997	1998	1999	2000
Washington, D.C.	San Francisco	Washington, D.C.	New York
Chicago	Chicago	Dallas	Chicago
San Francisco	Washington, D.C.	San Francisco	Washington, D.C.
New York	Dallas	Atlanta	San Francisco
Dallas	New York	Chicago	Dallas
Atlanta	Los Angeles	New York	Atlanta
Los Angeles	Denver	Los Angeles	Los Angeles
Denver	Atlanta	Kansas City	Seattle
Seattle	Seattle	Houston	Denver
Phoenix	Philadelphia	St. Louis	Kansas City

Source: 1997 and 1999: Moss and Townsend (2000); 1998: data compiled by Sean Gorman from CAIDA (Winter 1998); 2000: data compiled from *Boardwatch Directory of Internet Service Providers* 12th ed. (2000) and firm web sites.

Table 6

Population as a Predictor of Bandwidth in U.S. Urban Areas, 1997–2000

	1997	1998	1999	2000
Constant	0.40	–0.78	2.28	2.60
Population	0.815	1.185	0.500	0.641
(*t*-value)	(3.47)	(7.28)	(3.98)	(5.83)
F	12.06	52.97	15.84	33.94
Adjusted R^2	.381	.619	.438	.515
Number of urban areas	19	33	20	32

Note: Analyses were of log bandwidth for each year on log 1999 population.

of bandwidth. By 2000, these cities were intermediate hubs on broadband networks connecting larger cities, and massive investments in bandwidth on them exceed what could be accounted for by population alone. A further analysis that attempted to explain patterns of investment in Internet bandwidth indicated that in addition to population, the presence of doctoral-granting institutions and economic dynamism explain the interurban pattern of investment in Internet backbone networks (Malecki forthcoming).

The rise of New York and Chicago in absolute bandwidth connectivity masks the relative standing of these cities. Table 7 illustrates that it is the urban areas located in the central region of the United States that are serving as intermediate hubs in the transcontinental routes, much as they served as break-of-bulk points in earlier transportation networks. Four cities have more than double the bandwidth their population would suggest, on the basis of only the 32 cities in Table 4. Expanding the list to the top 100 metropolitan areas shows that the phenomenon of centrally located and intermediate-size cities having high amounts of bandwidth continues: the average bandwidth per 1,000 population for the top 100 cities is 19.6 Mpbs, scarcely lower than the 19.83 Mbps for the top 32 cities alone. Well below-average bandwidth/population ratios are seen in the large eastern cities of Boston, Philadelphia, and New York; in the western cities of Phoenix and San Diego; and in the manufacturing-belt cities of Detroit and Pittsburgh. In Florida, Orlando, as the hub connecting both Tampa and Miami, is better connected than either with bandwidth. Charlotte serves as a similar midpoint between Atlanta and Washington, D.C.

Network bandwidth, as a form of infrastructure, is supplied in response to demand—actual or anticipated—for data transmission. However, the demand for Internet bandwidth is a difficult concept to define, let alone to measure. There are perhaps three interrelated dimensions: network economies, agglomeration economies, and the density of users (business and residential). A network is more valuable the greater the number of users (or other nodes) on the network (Katz and Shapiro 1994; Lehr 2001). Some locations are more productive or advantageous than others because they are also the locations of other networks. Through interconnection, a network is able to reach or serve locations on other networks. Interconnection, therefore, translates into a larger number of alternative locations that can be reached expeditiously via other networks (in addition to one's own).

Bandwidth is not the only indicator of the emergence of the Internet in the spatial economy. Domain names are an equally common measure (Moss and Townsend 1997; Zook 2000a, 2000b). As Zook (2000b) pointed out, the use of domain names is especially problematic at the national level, where generic top-level domain names, such as .com, .net, and .org, are not specific to any country. However, Zook (2000a) presented what is perhaps the most complete analysis of the geography of domain names in the United States and

Table 7

Bandwidth Connecting U.S. Urban Areas on 41 Backbone Networks, 2000, per 1,000 Population

Rank	Urban Area	Bandwidth (Mbps) per 1,000 population
1	Salt Lake City	68.72
2	Kansas City	50.85
3	Tulsa	44.40
4	Denver	40.34
5	Atlanta	38.68
6	Dallas	37.39
7	Seattle	31.60
8	Portland	31.26
9	Las Vegas	30.71
10	Orlando	29.66
11	San Francisco	29.35
12	Austin	28.69
13	Washington, D.C.	28.29
14	Cleveland	27.76
15	St. Louis	26.87
16	Indianapolis	25.69
17	Sacramento	25.67
18	New Orleans	25.11
19	Charlotte	25.01
20	Chicago	24.95
	Average of 32 urban areas	19.83
21	Houston	17.91
22	Phoenix	15.22
23	San Diego	14.91
24	Tampa	13.30
25	Boston	13.24
26	Philadelphia	12.36
27	New York	11.60
28	Miami	11.35
29	Pittsburgh	10.80
30	Minneapolis	10.35
31	Detroit	9.74
32	Los Angeles	8.77

concluded that, over time, there has emerged a stronger connection between Internet content and information-intensive industries than between Internet content and computer and telecommunications technology industries, although the latter was not measured by backbone connections or bandwidth. While the largest concentrations of domain names were in the New York, Los Angeles, and San Francisco urban areas, the highest specialization ratios (similar to locations quotients) were found in San Francisco; Provo, Utah; Denver; San Diego; Washington, D.C.; Austin; Boston; Santa Barbara; Las Vegas; and Portland (Zook, 2000a, 416). Kolko (2000) also analyzed domain density in U.S. cities from 1994 to 1998 and found several variables, such as income and education, that, in addition to population, account for the location of domain names. He found that domain density is higher in larger cities, even after controlling for other variables, and that the relationship with population grew stronger over the five years. Moreover, domain density is higher in more isolated cities, those distant from cities of similar size, such as Denver, Miami, and Seattle.

The tremendous growth of bandwidth linking the major cities of Europe and the United States presents a second overriding issue surrounding the Internet: that of the interconnection of the various backbones. The interconnection points are another key aspect for which geography is of growing significance. Once again, agglomeration and network externalities favor large cities.

Interconnection

The counterpart to what we call interfirm linkages are the transactions that connect the various individual networks into the Internet. Telecommunications flows are somewhat difficult to reconcile with the conventional topic of linkages for two reasons. First, there is a lack of data on the transactions that take place via the Internet via e-commerce and other systems and, second, there is a similar lack of data on the evolving system of interconnection within the Internet industry.

The original Internet had no hierarchy of hubs; interconnection was complete. The popular view of these transactions, reflecting the situation as it was about a decade ago, is of relatively few networks agreeing on a mutual access point, installing the necessary equipment, and then monitoring traffic to manage load levels. This process was called *peering* because it was a connection between two equal, or peer, networks. Billing mechanisms for data traffic flows of the sort common to voice traffic still do not exist, a fact that has kept the cost of Internet access low. To maintain end-to-end service through multiple providers, Internet interconnection has become more critical: "as providers strive to improve QoS [quality of service] within their own domains the missing piece of the jigsaw will be the interconnect space between them which includes peering policies" (Bartholomew 2000, 37). The trend toward oligopoly and unequal power relationships has had three principal effects. The first is a billing mechanism, such as an item on monthly telephone bills for digital subscriber line (DSL) accounts with local telephone companies for Internet connection to backbone firms, such as WorldCom (UUNET), for access to the Internet. The second effect is the growing implementation of transit charges, or hierarchical peering—charging for interconnection. The third effect is the emergence of an industry to facilitate peering and interconnection.

Peering and financial settlements are the core of interconnection. An ISP must pay for knowledge of the routes that can take data onward or upstream in the Internet. "Routing information is not uniformly available" (Huston 1999a, 561). *Peer-to-peer bilateral* interconnections are private peering points established between large firms that see themselves as equals (thus the term *peer*) (Bailey 1997). Private peering has become so common that many backbone providers have left the public Network Access Points (NAPs) and refuse to peer with smaller network providers. For small companies to get their data to a nonpeering provider, they must pay transit fees to stay connected. The two-party contracts define a *hierarchical bilateral* interconnection, also called a *transit* or a *customer-provider* relationship, the most pervasive interconnection model in today's Internet. In general, however, the large networks do not make public their peering criteria under nondisclosure agreements—nor are they required to—keeping smaller ISPs at a disadvantage (Bailey 1997; Kende 2000). The technical aspect of interconnection is that ISPs that are able to interconnect exchange routing entries that enable traffic. Upstream routes are learned from upstream ISPs, such as backbone providers, only as part of a transit service contract executed between the ISPs and the upstream providers (Huston 1999a, 555–6).

Interconnection originally took place at public interexchange points, or NAPs. In the United States, four NAPs were established by the National Science Foundation (NSF) when it turned over operation of the Internet to the commercial sector in 1995. These NAPs were located in Chicago, New York (actually in New Jersey nearer to Philadelphia than to New York), San Francisco, and Washington, D.C. Predating the NSF-established NAPs, the Commercial Internet Exchange (CIX) was established in 1991 for interconnection of the growing number of commercial networks that served business clients; a similar exchange in the United Kingdom, LINX (London Internet Exchange), was established in 1994.

Table 8 shows that the degree of interconnection at the NAPs has been less than complete in recent years. Only Metropolitan Area Exchange-East (MAE-East), in the Washington, D.C., area, and MAE-West in San Jose, California, have been interconnection points for all major backbone networks. All 38 backbone networks (3 of the 41 in 2000 did not list any public interconnection points in the United States) presently interconnect at both MAE-East and MAE-West. The other two original NAPs, in Chicago and the New York area, are noticeably less used—the Chicago NAP by 31 networks and the New York NAP by 24. Indeed, it is a set of private Internet Exchange (IX) points that have become increasingly important in recent years. Table 8 illustrates the importance of private IXs in the case of the Palo Alto Internet Exchange (PAIX), which has become increasingly used by the backbone networks as a private peering point. Both PAIX and LINX claimed over 100 members in November 2000.

A particularly important set of hubs in the Internet is the IX point, where individual networks interconnect, mainly by private interconnection. TeleGeography's (2000b) directory of IX illustrates the uneven global geography of IXs (see Table 9). IX points may be a response to extant or future demand or an example of attempts to reap first-mover advantage within a region. In fact, network externalities accrue to both networks when interconnection takes place (Varian 2000). Nearly all of the *alpha* world cities are in the top tier of IX point locations. Compared to its *gamma* (third-tier) status in producer-service networks, Amsterdam is among the most wired cities in Europe; Stockholm is also relatively stronger in Internet connections than in producer-service firms.

Private peering has changed the Internet from a universal good to one controlled by commercial interests (Angel 2000; Huston 1999b; Thomas and Wyatt 1999). Private peering is particularly prevalent among the largest and oldest backbone providers, including Cable & Wireless, GTE Internetworking (now Genuity), PSInet, Sprint, and UUNET (part of WorldCom).

Table 8

Number of Backbone Networks Connecting at Public Network Access Points (NAPs)

NAP	1998 (of 36 Networks)	1999 (of 41 Networks)	2000 (of 38 Networks)
MAE-West (San Jose)	35	39	38
MAE-East (Vienna, Virginia)	36	40	38
Ameritech Chicago NAP	21	30	31
Sprint NAP- New York (Pennsauken, N.J.)	20	27	24
Number of networks at all four original NAPs	13	20	19
PacBell San Francisco NAP	21	27	24
PAIX-Palo Alto	13	20	21
MAE-Dallas	0	5	12
CIX-Santa Clara	16	11	6
MAE-LA	5	6	4
PacBell Los Angeles NAP	1	0	2

Source: Compiled from data in the *Boardwatch Directory of Internet Service Providers*, (Winter 1998), 11th ed., 1999, and 12th ed., 2000.

Table 9

Internet Exchange (IX) Points by Region

Continent	Number of IXs	Internet Exchange (Location) and Number of Internet Service Providers Connected
Africa	2	Capetown Internet Exchange—11
Asia and Middle East	40	HKIX (Hong Kong)—49
		JPIX (Tokyo)—36
		iIX-JKIX (Jakarta)—35
		L2IX (Seoul)—32
		THIX (Bangkok)—27
Europe	78	LINX (London)—82
		AMS-IX (Amsterdam)—71
		M9-IX (Moscow)—54
		DeCIX (Frankfurt)—51
		SFINX (Paris)—47
		VIX (Vienna)—43
		BNIX (Brussels)—30
Latin America	5	Internet NAP (Bogota)—12
		Chile NAP (Santiago)—9
North America		
Canada	5	TorIX (Toronto)—11
United States	94	MAE-East (Washington, D.C.)—116
		Chicago NAP—93
		MAE-West (San Jose)—83
		PAIX (Palo Alto)—80
		New York NAP (Pennsauken, N.J.)—32

Source: Based on TeleGeography (2000b) and TeleGeography (2000c, 120–1).

These firms are the members of an "old boys' network" that peer equally with each other, splitting the cost evenly, because they have similar networks and traffic patterns. Smaller players can connect to their backbones via high-speed access lines, paying for a transit link to make the connection (Gareis 1999; Kende 2000). These payments, called "settlements," are perhaps the greatest "pressure point" in the ongoing evolution of the Internet (Kahin and Keller 1997; Thomas and Wyatt 1999). Although data are extremely difficult to come by, a Digex source cites $30,000 per site per month as the access fee charged by Sprint (Gareis 1999). The large players are well connected to one another, typically through private peering (Gareis 1999). Interconnection and settlement agreements make the Internet a hierarchical infrastructure more akin to telecommunications than to the Internet's image of a flat democratic network of networks (Frieden 1998, 17). It is not only the "old boys" that peer privately, however. In 13 of 31 networks in Gareis's (1999) "peering snapshot," private peering accounted for 50 percent or more of all interconnections, based on trace routes to 1.2 million destinations in mid-1999, and private peering represented 33 percent or more of all interconnections on 19 networks. The levels of traffic passing through private peering points are much higher: Gareis (1999) reported that Qwest and Savvis send 90 percent of their traffic through their private peering points.

Private peering, secondary peering—private interconnections between smaller networks—and multihoming—users and ISPs connected to more than one backbone—insert complications into simple models of interconnection (Bartholomew 2000; Besen, Milgrom, Mitchell, and Srinagesh 2001; Crémer, Rey, and Tirole

2000; Marcus 2001). In effect, the Internet has evolved beyond the simple hierarchical model of the past (Huston 2001). Kavassalis, Bailey, and Lee (2000) suggested that the change—from a hierarchical system to one of market coordination in which several market interface transactions exist (Lehr 2001)—is a shift toward flexible specialization, a major trend seen in other industries during recent decades (Amin 1994; Piore and Sabel 1982; Storper and Scott 1992). However, the interconnections among networks are not public knowledge and are among the many unregulated phenomena of the Internet.

Most traffic among major universities in the United States, Europe, and Asia travels a different path, one that avoids the issue of private peering. Internet2 uses a network called Abilene, which "is an advanced backbone network that supports the development and deployment of the new applications being developed within the Internet2 community. Abilene connects regional network aggregation points, called "gigaPoPs" (UCAID 2002a). Peer networks of Abilene include a host of academic networks around the world, including APAN/Transpac (the Asia-Pacific Advanced Network Consortium), CA*net-3 (CANARIE's advanced Internet development organization), CERNET (the China Education and Research Network), DANTE (the Delivery of Advanced Network Technology to Europe), JANET (the UK Academic and Research Network), NORDUnet (the Nordic countries' network linking universities), and SingAREN (Singapore Advanced Research and Education Network), among others (UCAID 2002b). Therefore, traffic from U.S. to British universities travels on the Abilene backbone to New York, where JANET peers with Abilene. Traffic to most Asian universities travels via Abilene to interconnection points in the San Francisco area. Connections to private universities, such as Clark University and INSEAD, the international business school located outside Paris, do not use Abilene, but instead travel entirely via commercial networks.

Other than by trace routing, to determine whether and where private peering takes place is difficult at best. The hypercompetitive nature of the telecom industry has meant that few details are available on the relationships—the linkages—between the various companies involved. Gareis (1999) included (now-dated) data matrices of the number of private peering connections among 30 firms. The three largest firms account for 35 percent of all private peering among the 30 firms: UUNET accounts for 86 of the total of 534 connections; Sprint, 58; and Cable & Wireless, 41, or a total of 185 private peering connections, some of which are with ISPs outside the United States, such as Ebone, EUnet, Telia, and Telstra. What such data do not indicate are the interconnections among nonpeers, or the interconnections based on settlement agreements or transit charges. It is also evident from LINX peering details (LINX 2001) that the "old boys" do not peer with a large number of other members of the exchange. The small number of peering connections suggests either that the firms prefer not to disclose peering partners or that interconnection is taking place elsewhere—probably in one of several neighboring facilities to which LINX interconnects at London's Docklands.

Colocation: An Industry to Facilitate Linkages

A large number of firms have been established to offer similar services, including colocation and private peering. For-profit IX points, such as PAIX, have long provided an alternative to the NAPs, although not necessarily with less congestion. Increasingly, private IXs have been established for private interconnection, such as Telehouse's NYIIX and SIX in Seattle, both of which appear among the largest IXs in the world (TeleGeography 2000a). Telehouse, established in London in 1990, now operates one Telehouse facility in Frankfurt, one in Geneva, two in London (one, the original facility at the Docklands), and two in Paris, in addition to NYIIX in New York and LAIIX in Los Angeles.

The growth of this industry to facilitate interconnection—alternatives to both public access points and local telecommunication networks—has been remarkable. At the upper tier of this industry are privately developed IXs and MAEs, all of which facilitate private interconnections. The success of PAIX has led the IX's new owner, Metromedia Fiber Network, to build PAIX-East in Vienna, Virginia, as well as facilities in Seattle, Dallas, Atlanta, Los Angeles, and New York. Below the IX tier is the booming colocation business, which has attracted real estate firms, network providers, and others to operate "telecom hotels" and carrier-neutral colocation facilities that enable network interconnection (Evans-Cowley, Malecki, and McIntee forthcoming). In the turmoil of the past two years, firms such as Intel have entered and left the data center market.

A glimpse of the extent of the business is seen in Table 10, which lists the cities chosen for the facilities of 18 colocation firms; several other firms offer facilities at one site or multiple sites in a single city. The table shows that the urban hierarchy is reinforced by these facilities, which respond to both demand and supply factors. Demand is indicated by the larger number of competitive local exchange providers in large metropolitan areas (Malecki 2002) and from the larger number of local Internet-based businesses (Moss and Townsend 1997; Zook 2000a). Supply, in the form of bandwidth and multiple fiber-optic connections, is also present in these areas, as seen in Tables 3 and 4. A second indication of local demand in U.S. cities is seen in the concentration of web design firms in a survey by *Internet World* (Design Survey 2000). Just four consolidated metropolitan statistical areas (CMSAs)—New York, San Francisco, Los Angeles, and Washington, D.C.—are the homes of 51 percent of 167 web design firms. The same four metropolitan areas stand above and apart from the others in Table 10.

Private interconnection has proliferated, and new services and industries have emerged to serve the phenomenon. Below the colocation tier is an amalgam of facilities, including data centers and web hosting facilities, operated by backbone providers, as well as by small ISPs. Greenstein's (1999) research suggests that 20.7 percent of all U.S. ISPs provide some web site hosting. Among national ISPs and especially among Internet backbone firms, web hosting appears to be less concerned about peering than about keeping clients plugged into the hosting firm's network and to provide services that firms find better to outsource. Data centers, likewise, are less concerned about peering than they are about providing services, whether around-the-clock management of operations which most firms cannot do in-house as cheaply, or network connectivity. For example, Intel had no network to trap clients onto, so it offered managed services plus colocation (Bernier 2000). AT&T, on the other hand, is primarily concerned with keeping customers on its network. Thus, there are a growing number of variations as classic telecom hotels have seen the addition of carrier-owned data centers and a new crop of "concierge floors" inside those hotels, operated by colocation firms (Branson 2000).

The choice cyberlocations are where data centers, server farms, and other facilities that depend on the Internet-related infrastructure tend to agglomerate or cluster. Strom (2000) identified three distinguishing characteristics of cyberbuildings: (1) multiple fiber connections to several different backbone providers and space inside for cables and gear; (2) facilitation for multiple ISPs to connect to each other inside, reducing the number of network hops; and (3) an aggregation of expensive equipment to facilitate fast switching and peering. In addition, Strom alluded to a fourth characteristic: Many of the buildings are far from being prime real estate; most are aging and in declining neighborhoods in the center or edge of downtown. Although a few new, custom-built buildings are being

Table 10

Urban Areas of Colocation Facilities of 18 Firms

Urban Area (MSA/CMSA)*	Current	Planned	Total
Los Angeles	12	4	16
New York	10	5	15
London	12	1	13
San Francisco	7	5	12
Washington, D.C.–Baltimore	6	6	12
Boston	6	3	9
Chicago	6	3	9
Atlanta	6	2	8
Dallas-Fort Worth	8		8
Seattle	5	3	8
Paris*	4	2	6
Tokyo	5		5
Miami	2	3	5
Orlando	2	3	5
Philadelphia	2	3	5
Portland, Oregon	3	2	5
Amsterdam*	2	2	4
Frankfurt*	2	2	4
Sydney*	1	3	4
Cleveland	1	3	4
Houston		4	4
Phoenix	1	3	4
Pittsburgh	1	3	4
San Antonio	1	3	4

Note: Only cities with four or more total colocation facilities are shown. Amsterdam, Frankfurt, Paris, and Sydney were allocated planned centers identified only for the Netherlands, Germany, France, and Australia, respectively.

constructed, many are recycled old factories, office buildings, and department stores.

The complex arrangements and coalescence of demand for several technologies has a geographic effect: to locate key infrastructure (routers, switches, and long-distance hubs) at common locations. These common locations are typically at or near (some of) the central offices of telephone carriers or at "carrier-neutral facilities." These locations are hubs of fiber-optic networks, are often the location of points of presence (PoPs), and therefore serve as private peering points where ISPs interconnect. They also provide access points for local demand, especially by midsize businesses and high-tech small firms that were never part of leased-line networks. "The collective behavior of dozens of backbone network companies has created a highly organized system. Although the Network Access Points established at the end of the NSFNet era were important in providing seed points for private networks to converge, we have seen commercial backbone providers establish private connections in these same regions as well" (Moss and Townsend 2000, 45). In only 11 cities in the United States, the PoPs of four interexchange carriers (all of which are also Internet backbone providers) are located within a single central office or wire center. These four (AT&T, MCI, Sprint, and Cable & Wireless) are colocated—facilitating private peering—in Anaheim, Austin, Atlanta, Cleveland, Hartford, Indianapolis, Kansas City, Minneapolis, Orlando, Pittsburgh, and San Antonio—all midsize cities well provided with backbone bandwidth (see Table 4). The agglomeration of bandwidth, PoPs, and other telecom infrastructure in these cities has made them attractive for the colocation industry (see Table 10). Of the 11, only Atlanta and Anaheim (part of metropolitan Los Angeles) are among the top 10 metropolitan areas in bandwidth.

Conclusion

The evolving network of networks and its network of interconnection and data center facilities has once again reinforced the urban hierarchy. Although a steady stream of optimists see ubiquitous communications as the salvation of rural and remote areas, the growth of new technologies "does not automatically result in the decentralization of economic activity" (Richardson and Gillespie 2000, 201). Urban agglomerations remain better connected to markets and to competitive product and service innovations. However, we still have precious little data on actual *flows* themselves—not only data transfer volumes but also time spent in data or voice communication, whether face to face; by telephone, e-mail, "instant messenger," or teleconferences; or in person-days (in specific locations) away from the office. Although these forms of contact are all electronic, they are not alike in their ability to transmit complex cues and other information (Leamer and Storper 2001). Mitchell (1999, 143) does not expect substitution of face-to-face contact:

> The various forms of local presence and telepresence, and of synchronous and asynchronous communications, have similar and sometimes overlapping uses but are not exact functional equivalents. They add value to interactions and transactions in different ways, consume resources of different kinds and at different rates, and are feasible under different sets of conditions. So they do not straightforwardly substitute for each other, and we should not expect a wholesale replacement of face-to-face interaction by electronic telecommunications.

The unregulated situation in the United States—the triumph of neoliberalism in the Internet age—has crossed the Atlantic (Kende 2000; Oxman 1999; Schiller 1999). Worldwide, but particularly in Europe and North America, investments in cyberplaces are being made by several firms simultaneously. The attraction of these firms to accumulated infrastructure suggests inertia but mainly represents rational market-oriented decisions. To a large degree, the evolving infrastructure of the Internet is reinforcing old patterns of agglomeration: the world cities are alive and well. At the same time, new technologies cause new "disturbances" that can result in the emergence of new clusters—perhaps particularly evident in the weightless context of an Internet world in which the cost of transport does not matter (Quah 2000). The prominence of Amsterdam and Stockholm in Europe and of Salt Lake City and Atlanta in the United States suggests that new clusters can emerge. London and New York remain important, if only because of the agglomerations of cumulative investment that they represent. Whether Tokyo will rise to its world-city status in Internet measures remains to be seen; Hong Kong and Singapore are credible competitors.

Policy is needed more, perhaps, within cities, where an array of "premium networked spaces" is emerging: new or retrofitted telecommunications infrastructures, "customized precisely to the needs of the powerful users and spaces, whilst bypassing less powerful users and spaces" (Graham 2000, 185). Graham attributed this emergence to four distinct processes: (1) the unbundling of infrastructure networks via privatization, with cherry picking of business clusters, such as financial districts and foreign firms; (2) the erosion of comprehensive urban planning and the construction of new consumption spaces developed, organized, and managed by property-led development bodies; (3) in residential areas, the construction of "infrastructural consumerism" (with geodemographic targeting to pinpoint concentrations of potentially high-spending customers); the tendency for infrastructural choice to be limited to certain social and spatial groups within the city; and (4) the presence of urban decentralization and the polynucleated urban region (with highways as the dominant form of transport). These somewhat distinct processes coalesce to create privileged spaces.

The fact that central-city buildings and districts are among the prominent IX points in many cities reflects the accumulated investment in prior networks that have served producer-service firms in central-city locations. In other areas, such as the northern Virginia suburbs west of Washington, D.C., and the Silicon Valley area south of San Francisco, more recent investment has concentrated a large amount of Internet-related infrastructure in the form of data centers and IX points. The prominence of established telephone network hubs (wire centers), which largely originated in an earlier era, with their concentrations of switches and other equipment for interconnection, is one element in this infrastructural inertia. For example, five sites in Manhattan and seven in Dallas have clusters of 10 or more switches in conventional telephone wire centers, well served with fiber-optic cables. Ongoing research is needed to determine the importance of these and other locations within several U.S. cities in the context of Internet interconnection.

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