NETWORK-BASED FUNCTIONAL GEOGRAPHIES

The concentration of connectivity has direct bearing on the functionality, efficiency, and vulnerability of the network. In an examination of the neuronal connectivity of the brain, Sporns and Tononi (2002) observe a variety of network patterns that are indicative of functional patterns of connectivity associated with specific perceptual and cognitive states. This functional connectivity occurs in the context of the broader anatomical network (the set of neurons and the corresponding synaptic connections at a given point in time) and suggests that different portions of the anatomical neuronal network are associated with the different functions of the brain. This is, arguably, similar to a transportation network in that different nodes on the network are functioning in several ways. In the case of the U.S. domestic airline travel networks in this study, the hubs serve as both origins and destinations, but also as bridges between otherwise disparate geographies (particularly international destinations in some instances). The result is that, as a function of their position in network space, different geographies take on different functional roles (e.g., different hubs connect different regions, certain hubs may dominate accessibility during certain times of the year, etc.). In that the network is dynamic and subject to change in response to both endogenous and exogenous factors, the functional geographies are consequently dynamic as well.

The connectivity of numerous real-world networks, including transportation networks, is often a function of the scale-free nature of the network in question (Zhao et al. 2005). While the scale-free configuration tends to ensure resilience to random network interdiction, a consequence of the hub-dependent connectivity is fragility in the event of the loss of the most connected nodes (Huang et al. 2006). Consider the example of Internet and telecommunications backbones addressed by Grubesic and Murray (2006). Grubesic and Murray observe that geography, specifically distance, tends to influence the formation of telecommunications networks in such a manner that their development follows something of a hub and spoke model. If a node were removed and that node were serving as a highly connected hub, then the disruption to network accessibility would have the potential to be significant (i.e., some portions of the network could become completely disconnected, while the remainder of the network would need to handle increased load). The removal of a node from a telecommunications network is somewhat analogous to the removal of a node from a transportation network. If a secondary airport is removed from the network, the overall effect on the functionality of the network is minimal. On the other hand, if a major hub is removed (e.g., due to severe weather as happens in many locations every year), the consequences can ripple throughout the entire system. Given the increasing dependence on hubs to sustain and increase connectivity over time (Figure 3.5), there is a commensurate increase in the impact on the viability of the network with the removal of any given hub.

An interesting dichotomy arises when one examines the configuration of network space relative to the configuration of the underlying geography. In the geographic space of the continental United States it would seem that, perhaps, the geographic center would tend to roughly correspond with the center of the corresponding transportation network. The network structure facilitates the calculation of measures of centrality (again, based on all pairs traversal of the network) and, interestingly, for several of the years in this study, Anchorage, Alaska, is the most central node on the network. This finding is echoed in a similar analysis by Guimera et al. (2005), who observe that Anchorage is one of the most central nodes in the global airline network, second only to Paris. In both cases, this raises the dilemma as to why a relatively unconnected node would have such a central place in either of the networks in question. Specifically, why would a geographic location that is relatively distant from many of the other geographic locations in the network have a central position in network space? Guimera et al. (2005) recognize that, due to geography, most Alaskan airports are connected principally to other Alaskan airports. Geographically, Anchorage serves as a consolidator of the many distributed communities and, in turn, as the connection for those communities to the remainder of the network and the continental United States. The "anomalous centrality" (Guimera et al. 2005) of Anchorage stems from the function of its geographic location in linking two parts of the nation, but the nature anomaly is not evident without inspection of both geographic and network spaces.

From a dynamic perspective, the geographic location that supports a particular network function is subject to change as the network structure changes. In a simulation of vertex and edge removal "attacks" on a network, Holme et al. (2002) suggest that fundamental measurements of network structure are subject to change as important edges are removed. In that measures of connectivity and centrality are subject to change as a function of changes to the network, the geographic locations that are playing specific roles with regard to network functionality are also subject to change. This is a very important dynamic geographic phenomenon that merits substantial exploration in a variety of domains.

DYNAMICS IN AND ACROSS NETWORKS

Though a single, minimally attributed, connection-based generative rule was used to create the functional geographic network describing airline travel, that network is by no means the only possible representation of the domestic air-transportation system. For example, the networks created by airline travel could be linked to the geographic areas they connect instead of the actual airports (e.g., Newark, LaGuardia, and John F. Kennedy airports all serve New York City), as in the analysis of Guimera et al. (2005). Similarly, distance between nodes in the network space could be simultaneously defined by geographic distance, percentage of on-time flights, or any number of other quantities. Furthermore, completely different networks that share similar nodes (e.g., highways between cities) could also be linked via the nodes in common. Thus, the entities serving as nodes in the network can be simultaneously incorporated into multiple network representations. In turn, these shared entities link different networks, each with potentially different spatiotemporal characteristics and, hence, different functional geographies. In the context of functional geographies, the shared entities that serve to link two or more networks can serve as the focal point for analysis that would have been impossible with any other type of representation. Recall the notion of the scale-free network and the commensurate ideas of preferential attachment. If a particular city served as a "hub" within the network formed by the airline transportation network *and* that city was located in a similar hub in the ground-transportation network, then the possibility exists for disruptions in one network space to move across network spaces and cause disruption in another network space.

The movement of a phenomenon through network space and, consequently, geographic space is known as percolation and is supported by underlying percolation theory. Frequently used in the context of understanding disease epidemiology (Moore and Newman 2000), the robustness or fragility of the Internet (Callaway, Newman et al. 2000), and even characteristics of species distribution (Brooks 2006), percolation theory is one basis for understanding how a network supports or inhibits propagation of phenomena through the network. Batty (2005) points out that gradual increases in connectivity can lead to sudden increases in percolation as the network becomes more connected. Given the possibility that one network might serve to induce connectivity in another spatially coincident network, however, functional geographies must be considered across multiple networks to get a true picture of connectivity. For example, ground-transportation connectivity could "bridge" two midsize, relatively close cities straddling an international border that do not otherwise have connectivity in the airline network. In the case of percolation of disease, information, or other phenomena, the network bridge induced by the proximal geography and connectivity as a function of the road network could significantly increase rates of percolation through the airline network.

The premise that a network between objects serves as a conduit of flow offers a number of opportunities for better understanding the dynamics occurring as a function of the presence of network connectivity. In the context of the network as an enabler, it is important to realize that the complexity of the network is not only a function of the structure of the network but also the interactions occurring across that structure. In the study presented here, though the structure of the network varies over the course of the time span of this study, the variation in the interactions occurring across that same network is substantially more significant. Keeping in mind that the complexity and connectivity of networks occurs in response to both exogenous and endogenous factors, consideration of such factors is vital for a complete understanding of the role of network connectivity and network dynamics in relation to both geographic and network-specific phenomena.

CONCLUSION

In the context of the analysis of dynamic geographic domains, the concept of what is a "network" is limited only by the lack of underlying, geographically centered theory regarding the relationships that form network and network-based interactions. Networks may be complex representations of the same geographic space but at multiple scales (Brooks 2006), may include representations of relationships based on proximity but also on aspatial characteristics (Béra and Claramunt 2003), and may serve to link explicitly geographic information with explicitly conceptual information (Sriti et al. 2005).

One intent of this chapter is to illustrate not only the validity of using network-based constructs to better understand dynamic geographic domains, but also to demonstrate that the integration of network approaches is not simply the horizontal transposition of one knowledge domain into the geographic domain. This chapter illustrates that increased understanding of geographic space using networks can, and should, occur based on contributions from physics (Barabási 2002; Newman 2003), psychology (Sporns and Tononi 2002), ecology (Brooks 2006), and geography (Grubesic and Murray 2006). Network-based understanding of dynamic geographic domains should evolve within the context of several complementary theoretical areas. Specifically, work in the area of ontologies (Agarwal 2005) is particularly relevant, as the basis for defining network generative rules should be based on sound understanding of geographic domains. In that substantial energy has been invested in issues relating to geographic and spatiotemporal representation (Yuan 1999; Hornsby and Egenhofer 2000; Peuquet 2001), new endeavors in network space should consider opportunities and gaps presented in earlier works.

Immediate opportunities exist to employ complex network theory to extend research in geography and, particularly, dynamic geographic domains. In the case of the air-transportation network and numerous other technical networks with a geographical complement, the evolution of the network itself is only one aspect of the dynamic nature of the system. Perhaps more important is that the network is a conduit to a large number of dynamic transactions or flows that occur along network edges. At any given moment in time and space, the precise structure of the network is determined by the instantaneous set of connections about to be completed (e.g., airplanes arriving at their destinations) and the set of potential connections about to be initiated (e.g., airplanes about to depart their origin). There is great need to understand how best to optimize the function of the network given exigent circumstances ranging from weather-related problems to terrorist interdiction. Any response to such a scenario would need to occur in the context of the evolutionary state of the network as well as the instantaneous status of the network at the moment of disruption. The importance of the interplay of geography and the functional spaces generated by the network requires explicit consideration in such a context, for the characteristics of the functional space are required to rapidly change from a configuration associated with the evolutionary structure of the network to one that emerges based on the nature of the instantaneous state change.

At a more fundamental level is the need for additional formalization of the relationship between geographic theory and complex network theory. Strogatz (2001), Hermann (2003), and Newman and Girvan (2004) all illustrate dynamic properties of complex networks that have the potential to significantly inform analysis of dynamic geographic domains. While Batty (2005), Grubesic and Murray (2006), and others have demonstrated the potential for integrating complex network theory and geography, clear articulation regarding the interrelationship between dynamic geographic domains and complex network theory is required. Inroads have been made in the area of visualization (Ruggles and Armstrong 1997; Fabrikant et al. 2004), but a number of challenges with regard to representation and analysis of would-be network datasets remain (Tobler 1987). This chapter illustrates that some properties of networks have natural geographic complements, while other properties are more a function of the nontrivial structures of the network in question — the extent to which these characteristics can be formalized should lay the foundation for a wide array of new analytic endeavors.

Once the potential relationships between geographic theory and complex network theory are further clarified, there exists a great deal of potential for directly integrating related analysis into existing geographic information systems. Network structures afford an alternative view to the map space that is prevalent in typical geographic information systems, yet many of the objects used to create nodes on networks are tied to geographic locations and represented in the GIS. Network-based analyses have the potential to shift the focus of GIS from representation constrained by location to representation with the innate capacity for supporting dynamic constructs. This shift, from the geography of location to the geography of relationship and interaction, has the potential of opening many new doors of inquiry and, ultimately, increasing our understanding of spatiotemporal phenomena and dynamic geographic domains.