

Chapter 5 – Conventional network theory

5.1 Introduction

Network theory is currently the focus of a great deal of attention, both in terms of academic research, and in application in the non-academic world. Based on a combination of social network theory and mathematical models, conventional network theory treats networked systems as collections of interconnected *nodes*. In this chapter, I shall discuss the origins and development of this conventional theory of networks, and the manner in which it has been applied as metaphor to systems and organizations. I shall also discuss in some detail the inherent problems of conventional node-based network models, demonstrating how they can influence the way that we think about systems. This is however, a partial account and does not claim to be an exhaustive treatment of network theory. I have highlighted the aspects of network theory that are, I feel, most relevant to my own research and which exemplify the literary context surrounding my own ideas. The chronology and detail of this account are drawn from a number of sources, but principally from Barabasi (2003), Buchanan (2003), Littlejohn (2002), Scott (2003) and Watts (2004).

5.2 The history and development of conventional network theory

Network theory originated during the 1930s in the social sciences and was considered to be primarily a social science tool until the late 1950s when Cartwright and Harary (1956) connected network theory with graph theory and mathematics. After that point, the mathematical research into network structure continued at a steady pace, resulting ultimately in our contemporary and conventional network models. The network theory as it exists today, which includes “small worlds” models is based upon some fairly complex mathematical models, although the core principles are relatively straightforward to understand. Despite the underlying complexity of modern network theory, the subject has become immensely popular, and modern network theory has become applied in many different domains, from computer networks, to biological ecosystems, to business management.

The original work on network theory was conducted by an informal group of German psychologists who specialized in “Gestalt psychology”. Gestalt psychology offers a direct contrast to the classical Cartesian/Newtonian

approach, and was one of the precursors of the systems theory view. In subsequent years however, network theory has become much more conventionalised, as the whole systems theories of the Gestalt scientists became mapped onto the more classically based graph mathematics. As a result, network theory has the potential to offer an interesting insight into the way that a model may develop “between” worldviews. In practice however, and despite the cries to the contrary of many network specialists, who claim that it does take a whole systems view, modern network theory has much in common with the classical Cartesian/Newtonian worldview. The details of how this is so will become apparent in my critique of network theory, which appears later in this chapter. But first we shall consider how modern network theory came into being.

There are two main threads to the research that has been carried out on conventional networks. One, to which I alluded above, relates to human *social* networks, and originated during the 1930s. The other thread, which began more recently, concerns the study of networks as *structures*, and has led to the development of *mathematical* models of network structure. These two threads have however become intertwined at stages during their evolution, with social networks informing the network structuralists and vice versa. With this in mind, I shall tell the story of the development of network studies on a single timeline, pointing out along the way how the approaches of the social scientists both differed from, and connected with the structuralists and mathematicians.

5.2.1 Social network theory

The psychologist, Jacob Moreno, was one of the members of the informal group of German psychology researchers, which first developed the concept of social networks. In 1937 Moreno published his own network model, which he used to analyse human social groups. Moreno was studying whether the psychological state of individuals within a group is related to the relationships between the group members (Scott, 2003). Moreno invented the “Sociogram”, a diagrammatic representation of the relationships between people in a social group. Typically, sociograms consist of dots, or “nodes” that represent people, with the relations or connections between them represented by lines.

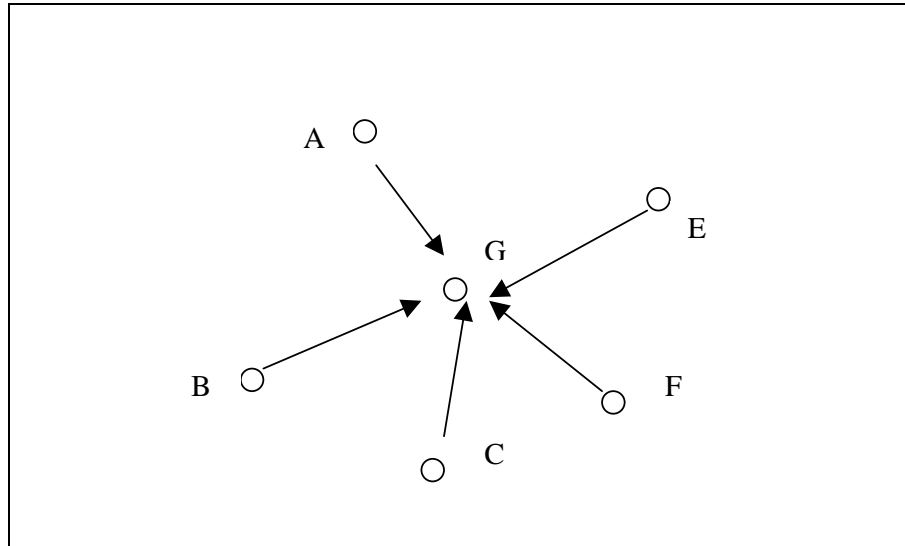


Figure 5.1. A typical Sociogram. Nodes represent people, arrows show the relationships between them.

Moreno's work initiated a line of research that dealt with the measurement of social networks, and which was ultimately to become "Social Network Analysis", a method for measuring and analysing social networks (Scott, 2003). The details of social network analysis will be dealt with in more depth in a later chapter of this thesis, as it is more concerned with practical methodology and analysis than with network theory. It is, however, worth noting here that the work initiated by Moreno psychologists branched off into two distinct threads at this point – the line that became focussed on social network analysis, and the line that was to become developed into contemporary network theory, which concerns much more than social networks alone.

5.2.2 Graph theory

The next significant development in network theory research didn't appear until some twenty years later, with the publication of a paper by Cartwright and Harary (1956). Cartwright was a sociologist, while Harary was a mathematician. Their paper made the claim that sociograms such as Moreno's could be analysed using a type of mathematics, known as *graph theory*. In mathematical terms, a *graph* is a structure or diagram consisting of points that are connected by lines representing the relations between them. Graph theory is a subset of mathematical calculations and formulae that describe these graphs. Up until this time, the social scientists who were working on sociograms had used *words*

to describe the relations represented by their diagrams. The significant contribution of Cartwright and Harary was to link the hitherto entirely qualitative sociograms of social science, with the quantitative analyses of graph theory.

5.2.3 Six degrees of separation

In the late 1960s, Stanley Milgram advanced network theory by a major step. Milgram, a Harvard sociology professor, was investigating what was colloquially known as “the small world problem”, after the popular, but as yet unproven hypothesis that within a social group any person could contact any other person through a surprisingly small number of links. Milgram set about testing this idea through an ingeniously simple experiment. He distributed letters to 160 randomly chosen residents of Wichita and Omaha in the United States (chosen by Milgram because they seemed suitably remote places in the U.S). All the letters were addressed to the same person, a stockbroker in Boston, NY. Along with the letters, Milgram sent a sheet of instructions directing the random recipients to forward the stockbroker’s letter either to the stockbroker himself (but only if they knew him in person), or to another person whom they felt was more likely than themselves to know him. Milgram wanted to find out how many steps on average it took for the letters to arrive. He suspected that this average would be a large number, perhaps as many as a hundred steps, and that if this was the case not many of the letters would actually arrive. By the deadline however, 42 of the 160 letters had arrived, and the average number of steps that the letters had taken was a mere six. Although Milgram’s experiment applied just to the United States, his findings gained great popular appeal, even becoming immortalised much later in a play by John Guare (1991). The title of the play was “Six Degrees of Separation”, and it was Guare who suggested that the six degrees rule might apply not just to America, but globally.

5.2.4 The strength of weak ties

In 1973 Mark Granovetter published one of the most influential papers to contribute towards modern network theory. It was titled “The strength of weak ties”, and developed upon the “Small Worlds” hypothesis proven by Milgram (Granovetter, 1973). As part of his Ph.D. research, Granovetter had conducted a survey of successful job applicants, in the Boston area of the United States. He was interested in how these applicants had found out about their new jobs, and the contacts that they had made to become employed. In interviewing

these people, Granovetter noted that in answer to his question about “whether the person whose information that led to a job was ‘a friend’”, often provoked the rejoinder: “No, just an acquaintance” (Barabasi, 2003). It was as a result of his findings, that Granovetter developed the idea that the significant links in a network are not the strong connections, but the weaker and more tenuous ones. He suggested that the strong ties within a network, for example those between close friends or family, who are frequently in contact with one another, are usually between mutually close groups of people. For example, in a family, there may be close ties between parents and children, and also between the children, in effect creating “triangulated” groups of strong links. Weaker links however, tend to connect *between* social groups. For example, we may have a friend who lives in New Zealand with whom we only make contact occasionally, perhaps just at Christmases. This friend however is likely to have an entirely different group of close contacts to our own, and our “weak” link puts us in connection with an otherwise far-removed social group; without this weak link, we might have no contact with these other people at all. In terms of job-hunters, Granovetter surmised that the close-knit groups of strong contacts were unlikely to provide opportunities of job prospects because they were in effect “closed”; they only have contact with each other, and the group is unlikely to be very large. Weak ties however put a job hunter in contact with a much larger network, where through tenuous links, they are more likely to encounter someone who they hadn’t heard about before, who was looking to employ someone.

Granovetter’s paper is also significant because he was the first to introduce the concept of the network *bridge*. A network bridge is one that connects between groups of close contacts that would otherwise be unconnected. This is exactly how the weak ties in a network act.

5.2.5 Watts and Strogatz' "Small Worlds" model

During the 1970s and 1980s, spurred on by the insights of Granovetter, the work on social networks continued, with researchers worldwide looking for small world phenomena in many different domains. Yet it wasn't until 1998 that another breakthrough in network theory was made, when Watts and Strogatz published a paper titled "Collective dynamics of 'small-world' networks". This paper was to become one of the most influential in the history of network theory. Watts and Strogatz, both mathematicians at Cornell University in New York, had set about trying to find a *mathematical* explanation for the small world phenomenon, focussing in particular on the organization of the *graphs* of small world networks.

What they found was that small world networks are neither random, nor regularly organized. Rather, they lie at a point between the two extremes. What characterises a small world network is the presence of *random* long distance ties, that directly interconnect otherwise distantly connected nodes.

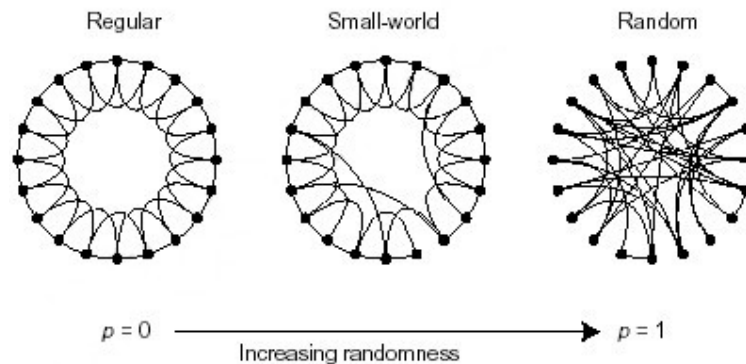


Figure 5.2 Different patterns of linking in regular, small-world and random networks (Watts and Strogatz, 1998)

One can immediately see a connection here between the findings of Granovetter, who identified the social importance of these weak, yet long distance ties, and the work of Watts and Strogatz, who identified the structural significance of these links.

After the publication of Watts and Strogatz' Small-World model, many other workers began looking for small-world structures. And indeed small-world structures were found in such diverse areas as language (Cancho and Sole, 2001), the World Wide Web (Albert *et al*, 1999), human sexual contacts (Liljeros *et al*, 2001) and cell metabolism (Jeong *et al*, 2000), to name but a few.

5.2.6 The significance of hubs

Currently, another key worker in the field of network theory is the physicist, Albert-Laszlo Barabasi (Barabasi, 2003; Albert *et al*, 1999 and 2000; Jeong *et al*, 2000). One of Barabasi's key contributions to the field of network theory is his work on the significance of *hubs*. As I explained earlier, Network Theory holds that networks are composed of entities, or "nodes" that are connected, with the connections between them being represented by solid lines. Through his research on the structure of the Internet (which he and his team had already discovered to have small-world structure), Barabasi found that in a small-world network there are often a number of nodes that are more *connected* than the others; they have far more lines connecting them with other nodes than the average node. Barabasi called these nodes "hubs" and postulated that they have greater significance than other nodes, since when they are removed from the network, the impact of their loss on the entire network is greater than nodes that have relatively few connections (Barabasi, 2003).

In terms of resistance to self-generated errors or minor internal failures, many nodal networks are actually quite robust. Research has shown that small-world networks are still able to function despite the deletion of many nodes, provided the nodes deleted are chosen at random (Albert *et al*, 2000; Callaway *et al*, 2000). If however, a targeted *attack* takes place that focuses on the hubs, the networks become very vulnerable; it only takes the removal of a small proportion of the hubs to cause the disintegration of the entire network structure.

5.3 Conventional network theory as a metaphor for systems and organizations

As I have mentioned, conventional network theory has now been applied in a great many different domains. In many of these situations it could be said that network theory was being applied as a *metaphorical schema* in these systems, that is to say, the systems were examined as *if they were* exhibiting network behaviour.

In biological science, network theory has been applied both on a macro level and on a larger ecological scale. Jeong *et al* (2000) studied the metabolic activities of biological cells. These researchers studied the internal metabolic processes of forty-three different species of micro-organism, and found that, not only were the patterns of processes in all the organisms structurally similar to one another, but also that the organization of these processes was structurally similar to that of non-biological “small-world” networks.

Meanwhile, Corner *et al* (2003) demonstrated that the spread of tuberculosis (which is transmitted through the air, like the common cold in humans) in a species of New Zealand possum, could be predicted through modelling the networks of social interactions between the animals.

In terms of human sociological behaviour, Newman demonstrated that the collaborative behaviour of research scientists may be described using network theory (Newman, 2001), while Liljeros *et al* (2001) have shown that on a sociological scale, human sexual behaviour may be described in terms of network theory. Liljeros points out that the actors in a social network who behave as “hubs” are significant, suggesting that the hub actors in a sexual network are likely to be those who are sexually promiscuous, and may be focal points within the network in terms of disease transmission.

Raab and Milward (2003), have made a distinction between overt, or “light” networks where people collaborate with the intention of ameliorating a problem or with other positive motives, and covert, or “dark” networks, where the motives are illegal or subversive. These authors looked at three kinds of “dark” network: heroin trafficking, networks of Al Qaeda terrorists, and military arms smuggling networks. They showed that these “dark” networks share some characteristics with “light” or overt networks. For example, both overt and covert networks share the same need for security. Covert networks, however, differ from overt networks in that they are structured according to the need for secrecy, and permit the use of physical force to achieve their goals. According to Raab and Milward, covert networks tend to be decentralized structures. They are also not as strongly reliant on hub figures as an overt network. Should a key figure be eliminated from a covert network (such as when a gang leader is captured and imprisoned), then there are usually others within the network who automatically fill his role.

In business organizations, network theory has been extensively investigated as metaphor. Morgan (1996), mentioned the use of networks as a metaphor for organizations. At that time however, Morgan suggested that the network metaphor fell within the wider model of “organization as political system”. Within this political framework, argued Morgan, organizations may be seen as loose networks of people who gather together for a common purpose, such as making money, developing a career, or some other common objective.

In subsequent years, many more have investigated network theory, both as an organizational metaphor and as model for organizational design. I mentioned a few of these in the previous chapter, such as Pavlovich’s (2003) “jazz” network metaphor. Others who have reviewed the state of research in the area include Borgatti and Foster (2003), and Palmer (1998), who both wrote detailed reviews on the use of network models in organizational theory.

Capra (2002) also proposes the use of a network metaphor within human organizations. According to Capra, the networks that exist within successful organizations are like natural living networks, such as those seen in natural ecosystems, which function as “self-generating networks of communications”. Capra goes so far as to suggest that the “living network” structure might be viewed as more than a metaphor, and that organizations might actually be understood *to be* living systems. This idea is somewhat contentious, and goes further than the scope of my argument here, as I don’t intend to explore deeply the boundaries between metaphor and reality in this thesis.

The network metaphor delves deeply into the way that we understand the structure of a system. Like the organic metaphor, conventional network structures are concerned with *relationships*. Conway *et al* (2001), explain that using network as metaphor in human organizations changes the imagery from a focus on *pairs* of dyadic relationships to one of *systems* of relationships. As in the organic model, metaphors based on conventional network theory are concerned with the way that the relationships within a network affect one another; it is realised that a change in one part of the network might affect other parts, and that the loss or gain of a single node might affect the whole network. Similarly, in conventional network theory the structures are non-hierarchical distributed systems. While some nodes may be more *powerful* than others, they do exist within a distributed system. Unlike in systems that have linear hierarchies, in a nodal network there may be alternative routes to a single node.

What makes the network metaphor distinct from the organic metaphor is the conceptual framework with which it is associated. The metaphor of “organization as network” is based on conventional network theory. Consequently, the network metaphor maps an established framework of concepts associated with network theory onto an organization. So, when applying a network metaphor, specialised network concepts may be brought into play. For example, a person in an organization may be viewed as a “hub” if they have contact with many other people. Or they may act as a “bridge” or “liaison” if other nodes need to communicate through them to reach the rest of the network.

5.4 A critique of conventional network theory

Clearly therefore, conventional network theory has become the focus of much research attention in recent years, and it continues to gain in popularity. As a research tool, conventional network theory can, and has been used to good effect for cross-disciplinary study. The appeal of the conventional network model is understandable. It brings orderliness to an apparently disordered world, reducing complex problems to a series of relationships that may be mapped diagrammatically. These diagrammatic maps may be analysed mathematically, often producing some neat answers, such as an indication of which nodes are more influential than others, or of how the network actually contains a number of sub-networks (Scott, 2003).

Nevertheless, conventional networks do have a number of inherent problems, which arise as a direct consequence of their topology and organization. Most significantly, conventional network theory is concerned *only* with nodal networks. Conventional networks are constructed from *components* that have been connected together. Like a schoolchild's chemistry model where balls with sockets are connected together with rods to represent a molecule, a nodal network comprises nodes that are connected together using point-to-point links. As we shall see throughout our discussion, this node-centred paradigm has had a major influence on the properties of conventional networks and the applicability of network theory. By comparison with the structure of *natural* networks, which I shall introduce in the next chapter, nodal networks are rigid and inflexible structures. This is so for both physical and conceptual nodal networks; a node-based organizational model brings about *inherent* rigidity.

The rigid nature of a node-based network is largely due the manner in which the focus, in conventional network theory, is on the nodes themselves. Nodes in a nodal network are *discrete* entities; they have finite boundaries that distinguish them from their surroundings. These are nodes that have been *abstracted* from their normal contexts. Conventional network theory represents any relationships that exist between these discrete nodes, by creating "links" between them. But, like the nodes, these links are also discretely defined; they are finite, point-to-point connections between otherwise independent nodes. The links don't branch, grow, bud, or flex. They go from *this point here* to *that point there*.

Think back for a moment, to Milgram's social experiment, which we discussed earlier in this chapter, where he asked American citizens to send letters to a particular stockbroker (Milgram, 1967). Milgram found that on average it only required connections between six people, six nodes on the network, to reach the stockbroker target. It was later discovered that this pattern also occurs in other societies and communities, such as the collaborative science research networks studied by Newman (2001), or in the Swedish "web of human sexual contacts" identified by Liljeros *et al* (2001). It didn't matter whether the target is a stockbroker, or a particle physicist, or a prostitute. Nor did it matter whether the context was American society, University research facilities, or Sweden – the small world structure was found in all of these contexts. The fact that small world networks can be found in such diverse environments suggests that the pattern may *not* be dependent on context. Does this not corroborate the argument that conventional nodal networks are fundamentally decontextualised from the start? One begins to suspect that it might be possible find a small-world network *anywhere*.

The problem is that while it might be useful to identify Small World relationships within a network, conventional network theory does not tell us much about a system as a whole. Nodal networks focus on the *relationships* between the nodes in the network, but not at all on the relationship between the network and its context. There is no inherent way of representing *context* in a nodal network model. In the conventional network model therefore, a significant aspect of the system has simply been excluded.

As I mentioned earlier, the nodal network model affects how we *think* about a network. One of the aspects of a network that is significantly affected by the nodal model is *communication*. In a nodal network the links that exist are all point-to-point; they reach from one node to another. As a result, communication in nodal networks is "transactional"; information is passed from one entity to another, via the lines that have been set out when the nodes were reconnected. This "point-to-point" communication mechanism is reminiscent of the Information Theory model of communication, which I have already discussed in Chapter 3. One will recall that in Chapter 3, I argued that Information Theory is a point-to-point model of communication, which, like conventional network theory, *abstracts* communicative processes from their contexts.

Another significant concept in the nodal network model is that of the *hub*. A hub is any node that has connections with more than one other node, and the hubs that are most highly connected act as focal points in a nodal network (Barabasi, 2003). According to Barabasi, nodal networks have robustness in the sense of being able to resist breakdown should the non-hub nodes be removed, but great fragility should the hubs themselves be taken away (Albert *et al*, 2000). It will become apparent when we discuss natural network structures, however, that hubs only have this significance in node-centred networks. Their pivotal role arises because the focus in a nodal network is *on* the nodes – so when one removes a key node, such as a hub, the effect on other parts of the network is great because there is nothing *to* the network other than decontextualised nodes and connectors. By contrast, as we shall see in the next chapter, many living networks are non-nodal flow-forms, rather than node based structures. When one removes a part of such a natural network the structure is usually flexible and resilient enough to be able to re-route flow around the damaged area, and even to forge new pathways that re-build the gaps.

The restrictions of the nodal network model also influence the network's patterns of growth and development. This again is a consequence of the rigidity of the lines that connect the nodes. The lines in a nodal network are always connected at either end to a node. The connecting lines only exist because they represent links *between* nodes, so they cannot end in "thin air". This means that the only way that a nodal network may grow is by the *addition* of new nodes. So for example, when a computer is added on to a company's Intranet (a classically nodal network), the new node (the computer) is connected to the network with a new link (an Ethernet cable).

Moreover, because the links themselves in a nodal network cannot branch, the network can only branch at a node point. This means that the pattern of growth in a nodal network is largely determined by the properties of the *nodes*. If a node has *capacity* for the addition of new links, growth at that location is possible, but if a node is fully populated with links, then growth at that node point must stop. A nodal network therefore has very little developmental plasticity. We shall return to this idea later, as it contrasts strongly with the natural network model.

5.4.1 The risks of applying a nodal network model to a non nodal system

The logic behind network theory is coherent and highly credible, and as a theoretical model of constructed *nodal* networks it produces some very rational explanations. The problem is that the answers provided by conventional network theory relate *only* to nodal networks, which means that its usefulness is limited. This is because, as I am about to explain in the next chapter, many naturally occurring networks are by contrast, *non-nodal* expressions of *flow forms*. There is a great risk that conventional network theory, based on nodal network structures, is being applied in situations where the structures are actually completely different. Where conventional network theory, with its node-centred analysis has been applied to living *flow form* networks, the result is often an erroneous picture of their organization, and indeed sometimes has the effect of causing them *damage*.

One such situation, where nodal network theory has been incorrectly applied to a living network is in the ecological concept of the “keystone species”. The biologist Robert Paine was the first to introduce the term, in the late 1960s (Paine, 1966). At that time, Paine was studying the shoreline ecosystems of the North American Pacific Coast. In a pioneering experiment, he chose a specific predatory starfish species (*Pisaster ochraceous*), which feeds on mussels, and removed all individuals of this species from a small (eight metre by two metre) area of shoreline over a period of several years. The impact of doing this was significant. Initially, the area became colonised heavily by barnacles. Later these were crowded out by a species of mussel, and eventually the site became dominated by mussels. As a consequence of the mussels’ grazing, most of the species of algae disappeared entirely. Over a period of several years, during which all of the starfish were removed, Paine found that the number of other species of organism in the community reduced from fifteen to a mere eight.

Paine surmised from this that all of these changes were provoked by the absence of the starfish, and that naturally they must play a vital role in the ecosystem. According to Paine it was the way that the starfish fed in patches that was most significant. Occasionally, the starfish would move into an area and completely clear it of mussels. However, because the starfish fed in a patchy manner, clearing only some areas, but never the entire population of mussels, over time the mussels would move in again to re-colonise the cleared patches.

Paine concluded that it was the predatory behaviour of the starfish that maintained the diversity and vitality of the community as a whole, and that is was therefore a “keystone species”, as without it the ecosystem fell apart. Later, authors such as Pimm, who reviewed a number of ecological studies where other keystone species had been removed, found similar patterns. Pimm noted that indeed often when a keystone species had been removed, the entire ecosystem had not been able to survive (Pimm, 1980).

According to conventional network theory, a keystone species is considered to be like a *hub* within the ecological network (Dunne *et al*, 2002). It is believed to have more relationships within the network than most other species, and therefore, as a network hub, has considerable impact on the whole network should it be removed.

The problem with this is that it's potentially a small step from this view, to classifying all ecological relationships according to how much their loss is “noticed” if they are removed. In reality, ecological relationships are much more complex than this. In a biological system, each and every species is dynamically interrelated, not only with the other species present, but also with members of it's own kind, and of course with the environment itself. Indeed Berlow *et al* (2004), who reviewed a number of studies on ecological keystone species, pointed out that a species that is key in the relational topology of the network, may not necessarily be key in terms of biomass, or of population dynamics. They suggest instead that the role of a species is more complex than a single-factor relationship. It seems to me that to suggest that one species is more “important” than another in the complex network that is an ecosystem, takes far too simple a view, and utterly misinterprets the paradoxical strength and fragility of what is a highly interconnected and living system.

5.5 Conclusions

So, to conclude this chapter I have discussed how models arising from conventional network theory, such as Small-World networks, have been used as metaphor and model within a wide variety of domains. Typically, conventional network models have been used to identify and describe relationships of power, influence and so on. I have described how conventional networks are node-focussed structures that *diagrammatically* represent the relationships or transactions occurring between contextually abstracted nodes. I have discussed how the nodal network model affects the way that we think about a network, and argued that conventional network theory tends to frame our concept of “network” in a manner that is inflexible and which limits the possibilities for growth.

Conventional network theory doesn't, however, describe every kind of network that exists, and in the natural world, one may find physical networks that are organized quite differently. In the next chapter, I shall introduce my own network model, which contrasts strongly with conventional network theory. This model is based on the organization of networks found in the natural world, and, unlike the node-centred transactional networks of conventional network theory, it describes networks that are produced as a result of a system's responses to *flow*.