A Computational Modeling Strategy for Levels

John Symons†

Rather than taking the ontological fundamentality of an ideal microphysics as a starting point, this article sketches an approach to the problem of levels that swaps assumptions about ontology for assumptions about inquiry. These assumptions can be implemented formally via computational modeling techniques that will be described below. It is argued that these models offer a way to save some of our prominent commonsense intuitions concerning levels. This strategy offers a way of exploring the individuation of higher level properties in a systematic and formally constrained manner.

1. Physicalist Approaches to Levels. The notion that the world is divided into levels is a vague but prominent feature of our commonsense intellectual apparatus. It also serves as the central presupposition of most attempts to articulate a metaphysical framework for nonreductive physicalism. In addition to its role in discussions concerning the ontological status of higher level properties, the notion of levels regularly figures in debates concerning the character of the special sciences. So-called higher level sciences such as economics and psychology are generally regarded as less authoritative than lower level sciences such as physics and chemistry. This relative inferiority of the soft or special sciences over the hard and maximally general sciences has been a matter of ongoing discussion in philosophy of science for decades.

Two familiar physicalist characterizations of the relationship between levels are prominent players in these discussions. The first presents nature as a system of strata. These strata are ordered in terms of ontological fundamentality and related to one another via reducibility. The archetypical example is Putnam and Oppenheim's (1958) compositional account of levels. A second widely held approach to levels is favored by functionalists and involves the appeal to some version of the realizability relation. While functionalists deny that composition and reducibility cor-

†To contact the author, please write to: Department of Philosophy, Worrell Hall 306, 500 University Avenue, University of Texas, El Paso, TX 79968; e-mail: jsymons@utep.edu.

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rectly capture the relations between levels, they usually share Putnam and Oppenheim's emphasis on the foundational role of microphysical facts.

This article presents a third way of looking at levels. Rather than taking the ontological fundamentality of an ideal microphysics as a starting point, this approach swaps assumptions about ontology for assumptions about inquiry. These assumptions can be implemented formally via computational modeling techniques that will be described below. These models offer a way to save most of our intuitions concerning levels and suggest a strategy for exploring the individuation of higher level properties in a systematic manner.

This third approach is motivated, in part, by the role of *levels-talk* in our everyday dealings with the world. In this context, talk of levels can be understood to result from the heterogeneity of inquiry. As we shall see, by assuming that inquiry takes some object or topic as a starting point and that inquirers are motivated by the goal of understanding the properties and relations that are relevant to its topic or object, we avoid the mistake of prematurely prejudging important open questions in metaphysics.

A single object of inquiry can be studied in a variety of ways. So, for example, the scientific community can simultaneously investigate the chemical, biological, economic, and social properties of some object or state of affairs. While researchers may harbor the hope that the results of all modes of inquiry are ultimately reducible to a suitably elaborated microphysics, in practice these hopes are relegated to the back burner. No matter what our metaphysical scruples, we are likely to acknowledge that a wide variety of kinds of investigation can generate true propositions; for the most part, metaphysical presuppositions concerning the reducibility of higher level sciences do not trump our interest in learning what those sciences reveal. We recognize, moreover, that generally our inquiries result in claims that are fallible. Even the assumption that inquiry begins with an object does not preclude the possibility that the existence of our initial object will be disproved at a later point. Instead, I assume that the structure of inquiry involves (at least) an initial focus on an object.

This article introduces a characterization of levels-talk in terms of models wherein distinct networks (each representing hypotheses concerning a level of laws and properties) are centered on a single object. For the models in question, the rules governing the behavior of each network will stand in for our hypotheses concerning laws, while the object in question is simply the target of inquiry. 'Object' is meant here in the broad logical or grammatical sense of something about which we can say something. So, by talking of object here, I do not mean to exclude processes and the like. Each network to which the object is related can be understood as a system of properties of a specific kind. The object will be related to the network insofar as it bears the relevant properties. The networks themselves will be governed by laws that apply to that kind of property. So, for example, social properties would be represented via a social network. An object is related to a network insofar as it bears properties that figure in that network. Thus, if some object has no social properties, then it would not be governed by the kinds of laws that govern social interactions. As we shall see, the object around which these networks are centered serves as the means by which the behavior of networks can interact. On this view, the relationship that an object has to a network (or level) is roughly equivalent to the relationship between objects and their properties. This relatively minimal characterization of the relationship between objects and levels offers an alternative to composition and realization.

2. The Legitimacy of Levels-Talk. One's opinion of the legitimacy of levels-talk is likely to be closely related to one's views concerning the nature of individuation and the ontological status of kinds. So, for example, criticism of levels usually rests on the claim that any putative difference between kinds of properties that are proper to specific levels is illusory. According to what we might call the eliminativist view of levels, any apparent distinctness is reducible in principle to characteristics of some single, ontologically basic set of objects and properties. For the eliminativist, the features of the ontologically basic stuff suffice to account for the appearance of levels. The sense of sufficiency intended here is ontological rather than epistemological. The eliminativist would suggest, for example, that in principle, any biological property can be cast as a disjunction of chemical or physical properties. In this sense, the eliminativist claims that while a biological property might be indispensable for explanatory purposes, it is ontologically otiose.

Contrary to eliminativism, experience teaches—or perhaps misleads us into believing—that objects can be encountered or manipulated in a variety of ways and that these ways fall into distinguishable kinds. For realists, genuine kinds are distinct by virtue of properties whose existence is independent of our epistemic or semantic dealings with the world. By contrast, antirealists point out that specific examples of natural kinds are almost always subject to doubt. While philosophers should perhaps be skeptical of realist claims with respect to specific cases, we are all committed to some degree of realism insofar as it is not possible to coherently claim that there are no mind-independent distinctions. The denial of mind-independent distinctions collapses insofar as it entails the denial of any real (meaning "mind-independent") distinctions between parts of the mind. It is difficult to argue for antirealism without referring to the distinction between the subject of an illusion and the illusion, or between the source of the representation and the representation itself. Such natural distinctions are required in order to make the antirealist case. The existence of at least some distinctions, let's call them natural differences, seems incontrovertible. However, some commitment to natural distinctions or kinds is not enough by itself to support an argument for the legitimacy of levels. The challenge for nonreductive physicalists or emergentists involves explaining how we can move from the claim that there are genuine distinctions in nature, to the more robust claim that reality is organized into levels or, more strongly, that there are genuinely new things that appear over the course of natural history.

Given the usual physicalist account of individuation, any genuinely new things that might emerge would do so only insofar as they exhibit causal powers that are not had by their constituents or their predecessors. Thus, from the nonreductive physicalist perspective, the most important challenge to a meaningful account of levels is the problem of epiphenomenalism. If we are concerned about the reality of the higher level properties, then we might worry that a corollary of epiphenomenalism is the collapse of any metaphysically real (meaning nonconceptual) distinction between levels.

While the question of levels has been tangled up with worries over the reality of so-called higher level properties, this is only one aspect of the issues involved in reconciling our intuitions concerning levels with our metaphysical and scientific framework. For example, talk of levels is not simply a matter of scale or of part-whole relations. Even in the case of a single object, ordinary experience tells us that there are often a variety of levels in play. My surgeon may treat me like a machine while I am on the operating table, but at the grocery store she ought to treat me like a person. Likewise, as philosophers of mind have emphasized for nearly 4 decades, the structural and functional properties of an object are generally distinguishable, such that, for example, the functional role of a tool is distinguishable from the physical properties of its constituents: We can accurately describe a particular spoon as a piece of plastic with certain physical properties or as an artifact that plays a specific culturally defined role. In the case of my surgeon and the spoon, the issue of levels involves the existence of distinct sets of properties and their relation to a single object. In these cases, the things in question, the utensil and I, are assumed to exist. Thus, rather than being concerned about the possibility that the properties in question could be rendered epiphenomenal via causal preemption of some sort, it is perhaps more natural to cast the problem of levels differently here. In these cases, the problem involves determining how, or whether, distinct kinds of properties are related to one another. The problem of understanding the relationships between types of properties will include cases where the relationship between types of property is orthogonal to the kinds of solutions that might be available via compositional reduction. So, for example, in cases of noninteracting properties, compositional reduction is not directly applicable and certainly fails to shed any significant explanatory light.

Unlike the argument for the legitimacy of higher level properties, the notion that objects can possess properties of different kinds needs relatively little defense. As we saw above, even a strong antirealist position should admit of at least some natural differences. Therefore, the burden for the claim that objects can possess different kinds of properties is considerably lighter than the claim that there are genuinely "higher" level properties.

Next, let us consider the possibility that objects can simultaneously have noninteracting properties. The fact that they do not normally interact would, of course, be grounds for considering them to differ in kind. So, for example, whether a surface is round or triangular is not necessarily relevant to its color. One can imagine that in cases of this sort, each distinct kind of property is governed by laws that are specific to its kind. In this sense, one can plausibly argue for the existence of distinct kinds of laws. While discussions of imagined kinds of laws and distinctions between kinds of properties are highly abstract, distinctions of this kind are embodied in practical terms as distinct kinds of inquiry. As we shall see in the next section, it is possible to provide a formal representation of the idea of a kind of property and a kind of law in terms of network models. Determining the precise metaphysical import of these models is beyond the scope of the present article. However, it is enough to establish that this third approach to characterizing levels can prove fruitful despite the well-known metaphysical challenges facing the advocate of higher level properties.

3. Networks. The so-called special sciences are concerned with specific domains and are often understood to lack the generality of physics. So, for example, economics begins with patterns and regularities at specific social scales. In these contexts, the apparently law-governed and patterned nature of economic transactions serves as the target for explanation.

Ordinarily, we ignore what philosophers see as the failure of fit between physics and the special sciences. So, for example, if we have studied a little economics, we tend to accept the applicability of some broad economic laws to social groups or institutions without necessarily feeling forced to regard the actions of individual persons as driven by purely economic considerations. A fortiori the microphysical constituents of an economic agent are thought to be completely untouched by economic laws. Our intuitive acceptance of levels-talk in these contexts runs into the paradoxical circumstance wherein the constituents of economic agents (whatever these agents turn out to be) are not governed by the economic laws that govern those agents. Likewise, the economic agent is independent, at least qua its economic agency, from the physical laws governing its constituents.

The problem is resolved once we consider the economic laws as limited to governing an object's economic properties, while the physical laws govern its physical properties. This, of course, is not a genuine resolution but rather a provisional agreement to allow the distinct sciences to pursue their business while the precise details of the ontological foundations remain unknown. It is not a resolution insofar as it only succeeds thanks to the suspension of the ontological fundamentalism that generates the problem in the first place. Nevertheless, let us assume that a single object or agent may participate in distinct networks by virtue of being a bearer of various kinds of ostensibly noninteracting properties. So, for example, some agent, let's call her Lola, has properties related to her social network; she is the friend of Zebedee, the enemy of Shadrach, etc. She also has physical properties that are subject to very different laws. These laws govern physical properties such as her spatio-temporal location relative to other physical objects, her mass, and so forth. We can characterize at least some of the changes in her physical properties in terms of a computational model; for example, as described below, we can imagine programming a cellular automaton that captures here motion relative to other agents in some region of space. The spatial model can also be treated as a network, but in this case, a cellular automaton representation offers a straightforward visualization of the agent's place relative to others. Initially, the social and spatial networks can be understood as modeling distinct levels of properties.

While she participates in both networks, it is not necessary to assume that this participation implies the presence of two distinct objects: a physical and a social Lola. Instead, Lola is a single object of inquiry and is the bearer of distinct kinds of properties. Notice that on this view, the interaction of distinct levels (networks) takes place via some object or set of objects that participate simultaneously in both networks. It is also conceivable that an object can participate in networks that have no influence on one another—the kinds of noninteracting properties discussed above (color and shape) could serve as examples here.

This general perspective admits of a formal treatment via advances in computational modeling. The study of networks and agents in mathematics and computer science provides an array of tools for the description and formal characterization of complex rule-governed interactions (Berkowitz 1982; Wasserman and Faust 1994; Freeman 2004). Returning to an agent like Lola, we can study and visualize her social properties using the kinds of social network models that have been in use for at least 2 decades (see, e.g., Scott 2000). For example, a model can simulate how her social properties might be governed by some relatively simple rules. There might be an upper limit on the number of friends she can have, there might be a minimal level of contact required in order to maintain a friendship, she might systematically avoid forming friendships with agents who possess particular characteristics, and so forth. Social network models incorporate rules in ways that give rise to results concerning communities, degrees of connectivity, the dynamics of social relations, and the like. The task of social network models is to study the implications of some candidate set of social rules in an abstract and controlled form. While discovering what rules and patterns there are in real human communities is an empirical task, these models can uncover unexpected features exhibited by social networks. In addition, some social network models provide recommendations and predictions concerning various sorts of intervention that might be possible with respect to human and nonhuman communities.

Social network models generally allow rules governing the maintenance of friendships to have inputs that are subject to factors that are not themselves subject to the laws governing the social network itself. For example, if an agent does not get a phone call from her friend in 10 months, they may be less likely to remain friends in the future. But the failure to make contact may have a nonsocial cause. Her friend's phone might not be working properly, or she might have misplaced her phone number accidentally. These nonsocial factors are not directly governed by the laws of the social network, and, in this sense, while they may play the role of constraining or modifying the network, they have the appearance of arbitrariness from the perspective of purely social considerations. These nonsocial factors introduce an additional dynamical component to the social network, serving as inputs (or variables) for the social laws to act upon. Needless to say, the values of such inputs cannot be deduced from the laws governing the social network.

Since the laws of a social network are not the fundamental laws of nature, there will be some aspects of the natural world that appear arbitrary given those laws alone. In this sense, social laws can be understood as holding ceteris paribus. However, notice that the only properties that are represented in and predicted by a social network are the social relationships between the agents; the network presents a dynamical representation of who is socially connected with whom. In this sense, these models aim to be exhaustive and maximally general with respect to the character of laws governing the social realm. Insofar as I have social properties, they will be governed by the finished network model provided by my ideal social science. Like classical mechanics, there may be imprecision with respect to measurements of initial conditions, but unlike classical mechanics (traditionally understood), there will be factors external to the social network that play a role in fixing those inputs or initial conditions. In any event, insofar as the laws governing the networks themselves would be exceptionless, these networks do not conform neatly to the usual debates over ceteris paribus clauses in scientific generalization.

While we can imagine having a complete account of the laws governing social properties in our ideal social network, Lola is not only a social agent. She has physical properties such as her mass and location in space-time and her velocity; she also has biological, epistemic, and moral properties. While the laws governing social properties may be complete, their scope is limited.

In recent studies, Jorge Louçã and I have focused on the interplay between social communication networks and geographical location. Specifically, we studied the reciprocal relations that exist in certain contexts between an agent's social/communication networks and its spatial location. We have modeled these relations in our case studies on cicada behavior and in human smart mobs (Louçã et al. 2007). Howard Rheingold introduced the expression "smart mob" to describe the concept of a "mobile ad hoc social network" (Rheingold 2002). Smart mobs are social networks where people communicate using mobile and wireless technologies. Smart mobs are becoming increasingly familiar due to their role in social and political expression. For example, SMS (short message service) communication was used to organize mass protests throughout Spain in the aftermath of the Madrid train bombings of March 11, 2004. Viral communication strongly spread through social networks mainly composed of friends, where trust between members of the network is extremely high. While there is an obvious "bottom-up" effect from spatial relationships to communicative relationships, our working hypothesis was that social factors also act in a systematic manner on the spatial locations of agents. In fact, the approach we favor, the networks' and agents' approach to levels, eschews talk of bottom-up and top-down influences.

Linking the social and geographical networks gives rise to novel features that are not solely the consequence of either network. Most of these features are fleeting and relatively trivial. However, on occasion, there is a persistent set of effects that are not the product of the rules of either network in isolation. In this context, "territory" is our term for an emergent feature that is detected via the study of the behavior of a socially and geographically networked agent. In ordinary usage, territories are understood to feature both geographical and social components. So, for example, an international border is a social or political construct that can serves as a physical constraint on our movements while simultaneously shaping our social relations. My movement through space and my social network are simultaneously modified by the action of the territory.

We have designed a generic model of smart mob dynamics, in which the viral propagation of communication through the social networks of individuals coexists with the coordinated movement of individuals toward attractive locations. Our model of smart mobs comprises two types of agents, individuals and attractors. Very briefly, when an individual finds an attractor, he or she propagates this information to all his or her friends; consequently, they will then move toward the attractor. Patterns in the tracks left by individuals can be analyzed for geographic effects of the social dynamics. The tools we developed in the smart mob and cicada models form the basis for the inter-network analysis of levels under consideration here. A complete description of our models along with some videos of the simulations can be found on our site: http://www.listaweb.com.pt/projects/cells/ModCom_test_site/index.html.

Our case studies provide an approach for exploring the manner in which collective behavior of the system in geographical space is shaped by constraints on communication. The next step involves providing a formal framework for understanding the interplay between networks more generally. In our research, we have focused on formalizing the process of identifying emergent properties that result from the interaction of communications networks and geographical movement. In more concrete terms, by associating patterns in different kinds of systems, we connect the notions of place, movement, and territory to social relationships as represented in social networks. To this end, we develop hybrid models that combine multiagent social simulation, cellular automata, and social network analysis.

Our goal has been to develop techniques that permit us to show how patterns from distinct networks are related via the participation of agents in multiple networks and to model the appearance of new features that emerge from their interaction. An operational goal of this research is to provide a set of tools composed of a methodology, algorithms, and a programming library, for the analysis of networks and for the identification of novel properties. The Z language (Spivey 2006) is used to formally characterize the approach. This specification language allows, on the one hand, the formalization of a set of concepts and the relations between those concepts, and, on the other hand, the possibility of straightforwardly converting the formal model into programming code. We formalize the following major steps within the framework: a pattern detection mechanism applied to social networks (ComNet), a pattern detection mechanism applied to a cellular automaton that models spatial motion (GeoNet), and the identification of links between patterns that were detected in the two networks. From here, we track the character of these links in order to ascertain whether they constitute meaningful and persistent regularities and whether they lead to distinctive effects in the two original networks.

4. Finding Territories. As mentioned above, territories play a role in modifying both geographical and social relationships. In this sense, territories have consequences in the structure of both networks. By formalizing the process of discovering links between patterns at distinct levels, we hope to provide a general approach to the identification of previously unrecognized emergent properties. In the models discussed above, the cellular automata serve as our way of representing the spatial or geographical dynamics of the agents in question. Obviously, alternative interpretations of what the cellular automata are representing are possible. The interpretation of the dynamics of the cellular automaton will be dependent on what it is that the researcher is attempting to model. A variety of systems of relations can be characterized as communications networks, and our approach is intended to be as generally applicable as possible.

Characterizing what we mean by effect in this context is technically challenging. It is possible, for example, to determine a baseline representation of the dynamics of the network in terms of eigenvectors and before examining the changes that are wrought by coupling the networks at agents. Detecting links between patterns in different networks is a significant technical challenge that we have taken some steps to overcome. In the specific case of the connection between social and geographical networks, we have formalized the following major steps:

1. Pattern detection mechanism applied to social networks (ComNet).
2. Pattern detection mechanism applied to cellular automata (GeoNet).
3. Identification of links between patterns that were detected in the two networks (Symons et al. 2007; Louça et al. 2007; downloads available at http://www.listaweb.com.pt/projects/cells/ModCom_test_site/index.html).

Patterns derived from ComNet and GeoNet can be associated to relate patterns characterizing different levels of analysis. The dynamics of each simulation is analyzed by determining the number of times each pair of structure from ComNet and trail map patterns from GeoNet occurs. Following methodology proposed by Newman and others (see, e.g., Newman 2000), we start by combining all possible *n*-tuples of specific trail maps and structures. Then we count how many times each *n*-tuple occurred. This allows us to infer a relationship between the two levels of analysis. Simulations where there is a salient effect between the two networks will present a larger number of occurrences when compared to pure random simulations (see Symons et al. 2007 for further details)

It could be argued that this result is obvious, as it arises from the rules of the model. However, the rules of the models themselves are not used to map the patterns in the results. Instead, the analysis is directed solely toward patterns that have been exhibited in the social network and in the trails left by agents in the cellular automata.

The discovery of novel features that result from coupling networks is a potentially fertile field of investigation. From a standard physicalist perspective, it will seem odd to claim that a territory is a genuinely novel feature of the world. While ontological considerations are beyond the scope of the present article, if we imagine our laws of nature reduced to the laws governing social networks and the motion of bodies through space, then the territory is not going to be reducible to the laws of either network in isolation. Because some agent has both geographical and social properties and because these properties differ in kind, we suggest that a new set of properties may emerge, namely, territorial properties. These properties are such that they can modify an agent's geographical and social properties. These are properties that result once the distinct networks are connected via an object or agent.

The notion that there are properties that result from the coupling of distinct networks is a feature of this approach that is likely to be appealing to emergentists. However, it is important to recognize that the approach under consideration here is epistemological rather than directly metaphysical in nature. For the purposes of the model, the criteria of individuation are straightforward; a territory is real insofar as it has effects on the distinct networks in which the agent participates. The agent's motion is shaped by territory insofar as the territory determines the probability that he will be in some region. Similarly, the agent's social relations are altered by territorial factors. His likelihood of remaining friends with other agents and the robustness of communities are influenced by territory. Relative to the existing networks, we understand territories as emergent properties that result from and, in turn, modify the spatial and social relations governing an agent.

5. Conclusion. It is useful to see the contemporary discussion of levels as consisting of at least four distinguishable topics: realizability, composition, distinctions between kinds of property, and the notion that there are irreducible kinds of explanation. How we revise our account of levels depends in part on how we determine the relative importance of these topics. So, as we saw above, eliminativists have concluded that non-reductive physicalist accounts of realization should be subordinated to strictly compositional considerations. Such a decision is motivated by the view that functionally individuated concepts, such as hammer or heart, do not constitute a genuinely distinct level for epiphenomenal or other worries.

Concerns about the epiphenomenalism of higher level properties rest on the assumption that one's intuitions concerning the ontologically fundamental level are more plausible than a realistic interpretation of the special sciences. Alternatively, we might decide that a compositional approach to levels can be sacrificed in order to do justice to our commitment to some prominent features of explanation and inquiry. This pragmatic approach to levels is not necessarily committed to antirealism with respect to ontology. Instead, it treats our claims about levels as subject to the same criteria of adequacy as other parts of our scientific theorizing.

In the opening section of the article, I suggested that the approach rests on epistemological rather than metaphysical assumptions. In the approach described above, agents are considered as the loci of interaction for networks. These networks can be understood as systematic expressions of our hypotheses concerning laws and properties of a specific kind. The core idea is to treat levels as networks, and agents (or objects) as the bearers of distinct sets of properties. The formal strategy sketched above provides a way of preserving a pragmatic account of levels while exploring the interplay between levels in a realistic spirit. By contrast, an approach that understands levels via a traditional set of ontological assumptions concerning the fundamentality of physics might be committing our ordinary intuitions about levels to too much and might miss a great deal of potentially very interesting science.

Some philosophers of science, most notably Nancy Cartwright (1983), have argued that all scientific inquiry and explanation takes the form of the construction of models in which the objects under consideration are in large part constituted by their role in these models. She contends that the generalizations that we derive from scientific models (including models of fundamental physical phenomena) have limited generality. In her recent work, she argues that such generalizations provide local truths concerning very restricted domains (Cartwright 1999). Without agreeing to her claim concerning the applicability of models, the network models of laws and properties described here appear to be subject to ceteris paribus generalizations insofar as they systematically screen off interfering conditions. However, there is an important difference: in the case of the networks under consideration here, properties and not objects are governed by the rules of the network in question. On her account, ceteris paribus models simply *do not apply* to nonidealized objects. The laws of gravitation do not apply to my bicycle but solely to point masses that figure in the gravitational model. By contrast, on the view presented here, the bicycle has a range of properties, some of which are best understood in terms of the gravitational model. In this sense, insofar as the bicycle has physical properties, physical laws apply to the bicycle. However, there are a range of other properties governed by other kinds of networks; for example the price of the bicycle would be governed by the kinds of laws that economics discovers.

REFERENCES

Berkowitz, S. (1982), *An Introduction to Structural Analysis: The Network Approach to Social Research.* Toronto: Butterworth.

Cartwright, N. (1983), *How the Laws of Physics Lie.* Oxford: Clarendon.

——— (1999), *The Dappled World: A Study of the Boundaries of Science*. Cambridge: Cambridge University Press.

Freeman, L. (2004), *The Development of Social Network Analysis: A Study in the Sociology of Science.* Vancouver: Empirical.

Louçã, J., J. Symons, D. Rodrigues, and A. Morais (2007), "Pattern-Oriented Analysis of Communication Flow: The Case Study of *Cicada barbara lusitanica*", paper given at the 21st European Conference on Modelling and Simulation—ECMS 2007, Prague.

Newman, M. (2000), "Small Worlds: The Structure of Social Networks", Santa Fe Institute working paper, http://www.santafe.edu/research/publications/wplist/1999.

Putnam, Hilary, and Paul Oppenheim (1958), "The Unity of Science as a Working Hypothesis", in Herbert Feigl, Grover Maxwell, and Max Scriven (eds.), *Minnesota Studies in the Philosophy of Science 2*. Minneapolis: University of Minnesota Press, 3–36.

Rheingold, H. (2002), *Smart Mobs: The Next Social Revolution*. Cambridge: Perseus.

Scott, J. (2000), *Social Network Analysis: A Handbook.* 2nd ed. Newberry Park, CA: Sage.

Spivey, J. M. (2006), *The Z Notation: A Reference Manual*. Hertfordshire: Prentice Hall.

Symons, J., J. Louçã, D. Rodrigues, and A. Morais (2007), "Detecting Emergence in the Interplay of Networks", in Goran P. Trajkovski and Samuel G. Collins (eds.), *Emergent Agents and Socialities: Social and Organizational Aspects of Intelligence*. Association for the Advancement of Artificial Intelligence Technical Report FS-07-04. Menlo Park, CA: AAAI Press, 86–93.

Wasserman, S., and K. Faust (1994), *Social Networks Analysis: Methods and Applications.* Cambridge: Cambridge University Press.