

SPACE-TIME REPRESENTATIONS OF COMPLEX NETWORKS: WHAT IS NEXT?

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*"I think the next century (21st) will be the century of complexity."
Stephen Hawking*

The research on complex networks may be traced back to previous work in "philosophy of organism" (Whitehead, 1925, 1929), neural networks (Arbib, 1995), cybernetics (Wiener, 1961), and cellular automata (Von Neumann, 1966). Complex networks are, without exception, dynamic, non-linear, and self-organising in nature, and have a scale-free structure in space (e.g. from quarks, atoms, molecules, material, objects, planet, to galaxies) as well as time (e.g. from nano-seconds to galactic time). This scale-free structure reflects a hierarchical organisation of nature that is capable of framing emergent properties of complex behaviour from relatively simple micro interactions between its components over time.

The development of scale-free structures is one of the central themes within complexity research because it goes beyond the established dualism of spatio-temporal database structures in GIS (e.g. raster versus vector, continuous versus discrete view of time) and moves further towards a more topological structure where relationships affect the probability of linking all components of a complex network. Therefore, a complex network is actually defined by its space-time relationships rather than by its constituent components. For example, in an economy, components might be consumers, firms and the state. Predicting whether the evolution of cooperation in commercial networks might collapse, or whether dense traffic will congest, involves issues with respect to how emergence, equilibrium, and change of relationships between these components can be modelled based on a free-scale network paradigm. Applications of complex networks in modelling micro-macro phenomena are currently in demand, and a vast literature can be found in physics, biology, psychology, geography, history, economics and environmental sciences. In particular, Manson (2001) provides an interesting effort at describing the evolution of complexity research and its application in the geographical domain.

Most of the theoretical research advances in developing scale-free-structures has relied on the generalisation of the Barabási-Albert model of dynamics of networks (Barabási and Albert, 1999). The primary research assumption is based on the use of a directed graph representation in

which nodes are weighted in a hierarchical structure but not mutually connected by a high density of links. Despite the fact that some of emergent properties are being understood, directed graph representations do not include critical time windows and geographical constraints among their realistic assumptions. For example, the Poincaré graph has been applied to determine if a network contains a strange factor, a value or a set of values towards which the system variables tend towards over time but never quite reach (Mainzer, 1996). However, the variables tend to moving along random different paths that are simultaneously constrained to a regular and geometric region of the graph.

Nellis (2005) has pointed out in his presidential address on "Geospatial Information Technology, Rural Resource Development and Future Geographies" presented at the Centennial Meeting of the Association of American Geographers, that "the real voyage of discovery consists not in seeking new landscapes, but having new eyes." One of the fundamental issues associated with having "new eyes" is to look at the development of a new space-time representation that can allow us to "see" the future evolution of complex networks on the surface of the Earth. Complexity invokes that everything is connected to everything else, hence a space-time representation will expose that near things are more connected than distant things (Waldo Tobler, First Law of Geography). By having the "new eyes", we will go beyond the two dominant network traditions that refer to the distinction between "groups" that are defined by some membership criterion (i.e. social network analysis) and "webs of affiliation" which are linked through specific types of connections (i.e. network governance approaches). A new space-time representation is needed to provide a conceptual pivot to deflect us away from the dualisms of structure/agency, subject/object, human/non-human and to move towards capturing the spatial and social logics of temporary organisational arrangements of complex networks (Grabher, 2006).

Over the past decades, the development of space-time representations has been extensively discussed by different research communities. In the Artificial Intelligence community, mathematical foundations have been provided to support the representation of changes in space (Vieu, 1997). In contrast, temporal database approaches have been proposed to support database models and query languages for the representation of mobile objects (Forlizzi *et al.*, 2000; Wolfson, 2002). Finally, studies oriented to the temporal extension of current spatial data models have been carried out by the GIS community (Cheylan and Lardon, 1993; Frank, 1994; Langran, 1992; Peuquet, 1994; Wachowicz, 1999; Worboys, 1994).

A number of modelling metaphors have been developed. These metaphors include the generic cause and effect relationship between an entity that has initiated a change and the entity that underwent such a change (Griffiths *et al.*, 2001; Pfoser and Tryfona, 1998), as well as the modelling geometric information at the most precise scale and then automatically computing all geometries at less precise scales using generalisation (Müller *et al.*, 1995; Weibel and Dutton, 1999). Representing predefined patterns has also been proposed to describe a process that can generate a change: (i) a pre-formatted complex attribute that can describe the processes which can account for changing the value of an attribute, especially the value of a spatial attribute; (ii) a causal relationship that can describe the processes involving several entities; and (iii) a process entity type that can describe complex processes that are composed of other related sub-processes (Chomicki and Revesz, 1999; Claramunt *et al.*, 1997).

Levels of detail in space-time representations have been previously addressed by research in multi-scale databases using hierarchical data structures (Timpf, 1998) and database views (Bédard and Bernier, 2002; Parent *et al.*, 1999). However, it remains for researchers to develop a conceptual multi-representation framework for processing and reasoning using geo-referenced data sets that are heterogeneous with regard to semantic and spatial resolution, and this research addresses a timely topic.

What is next? There are three complementary perspectives that should become research priorities.

Algorithmic Complexity

From an algorithmic complexity perspective, the manner in which geo-information is collected and used by the society at large will become a backbone issue of complexity research. Earth Observation Systems, geo-positioning and tracking devices, mobile sensor networks, and outcomes of models provide much of the geo-information being generated today. Very little attention has been given to the advent of digital text archives, which can provide *narrative knowledge* about spatial and temporal connections and interactions between systems, people, and places. Narratives provide a unique form of knowledge (Bruner, 1985). Computational knowledge models that attempt to capture geographical knowledge in terms of rules or deeper hierarchical networks tend either to become too abstract to be efficient (e.g. general domain ontology), or too case-specific to handle the behaviour of complex networks (e.g. taxonomy and digital gazetteer). Moreover, they also tend to equate incorrectly geo-referenced data sets with geographic knowledge, and their misuse can range from classifying remotely sensed images to considering the role of ecological community structure on biodiversity. Certainly, these shortcomings will become more apparent in narrative knowledge due to syntax, language, conceptualisation mismatch, style of writing, terminological mismatches, and encoding (format) of text sources. Previous research efforts have predominantly focused on text sources, and they usually combine Statistical Natural Language Processing, Computational Linguistics and Graph Visualisation methods for interpreting fictional (Piatti *et al.*, 2008), family-related (Van Vleck, 2007), and biological (Fry, 2004) unstructured text documents, or even mental ones, such as the "Visual Information Manager" called The Brain (TheBrain Technologies LP, 2009). An overview of current efforts in social, knowledge, business, food webs, political and transportation networks can be found in Visual Complexity (2009).

A space-time representation is vital to provide a means for exploring the structure of text sources simultaneously with geo-information. The main research challenge is to create a space-time representation in which the pluralism of sources can occur based on only one relevant *context of the explanation*. Scholars disagree about what context actually is and in what way it affects the processes of problem solving and learning in complex networks. Therefore, by contextualising space-time representations, the aim is to reinforce the thinking of knowing and mapping. We are particularly interested in the *movement context*, in the sense that the making knowledge is simultaneously the making of space, which in turn is made of movement. For example, in geography, hodology is the study of paths, in philosophy, the study of interconnected ideas, and in neuroscience, the study of the patterns of connections in the white matter of the brain (Wikipedia entry, hodology). A space-time representation is created in the process of moving through and

knowing a space. Consequently, knowing might be a form of travelling, of moving through space; and travelling, like knowledge, is also a form of narrative. These deeply hodological dimensions are now becoming apparent across a wide variety of areas of knowledge production, from the anthropological, through the scientific to the forensic and managerial (Turnbull, 2007).

Deterministic Complexity

From a deterministic complexity perspective, the research challenge relies on the process of explaining the meaning in a *chaotic system* of a variable always near instability actually moving to instability and thus destabilising the system (Haken, 1983). Periodically, instability can occur within complex networks, and to deal with such disruptions, a space-time representation needs to provide greater linkages between spatial and temporal variables. Although it is already clear that time cannot be treated as an extra spatial dimension and, so far, its linear and unidirectional nature – as opposed to the bi-directional nature of the space dimension – has not been properly investigated (Montello, 1993). As a result, a large number of time series are required to demonstrate that a system has deterministic complexity by incorporating negative/positive feedbacks, attractors and sensitivity to initial conditions.

Environmental disasters, disease epidemics, and wars constitute disruptions of social networks, and human exploitation of opportunities to expand networks, either spatially or in terms of the volume of activity, will also disrupt them. To understand these networks, human systems need to be embedded in a space-time representation that permits the interaction with other largely nonlinear systems such as climate and the evolution of disease organisms. Researchers will be challenged to adapt physical models of interacting particle systems and apply them to socio-economic systems. Responding to the challenge will demand a truly scale-free structure for a space-time representation. Also, researchers may discover important limitations to the adaptation of models from the physical sciences to human systems. One promising approach is the use of *fractals as self-referential patterns* having a tree structure regardless of the scale of observation (Mandelbrot, 1982). This scale-invariance of fractals has motivated geographers to model fractal patterns across scales of physical phenomena such as urban forms and coast lines (Burrough, 1991). Urban land use, for instance, may manifest a fractal pattern, but this knowledge only goes so far in aiding our understanding of the process by which it came to be that way. Many of the studies of fractal geometry are still at the early stages (especially those in geomorphology and cartography), and it is still difficult to apply fractals to socio-economical phenomena (Wong and Fotheringham, 1990).

Aggregate Complexity

From an aggregate complexity perspective, the main research challenge centers on understanding what principles govern the *self-organisation* of complex networks. Researchers understand well how, within systems with fairly simple interactions in equilibrium, individual interactions among local elements of a system can produce global patterns. In contrast, in complex systems, it is practically unknown what variables regulate the self-organising process. One interesting research direction will involve revisiting *agent based modelling approaches* to explore

how we can shift the paradigm of "micro interaction rules" toward "complex behaviour patterns". A new space-time representation will likely play an important role in challenging how micro interactions are related to emergent properties in agent-based models; especially those previously developed using cellular automata. They are tessellations structures that have allowed us to model a bi-directional interaction between adjacency cells, and they have been extensively used to model geographical phenomena ranging from ecosystems to urban morphology (Axelrod, 1997; Batty, 2005; Epstein, 2007; Gilbert, 2008; Gilbert and Troitzsch, 2005; Hewings *et al.*, 2001; Krzanowski and Raper, 2001).

Also, researchers need a new space-time representation to address the inverse problem: how can micro-interactions be inferred from complex behaviour patterns? Patterns are scale dependent, and they are *always* dependent on the context, which in turn depends on the levels of detail that can be used for predicting the interactions in complex systems. Emerging research on quasi-dynamical symmetry and perspective change has suggested that humans maintain a series of separable and embedded representations, rather than a single hierarchical representation of all known spatial environments. These representations in turn determine the course and form of economic and social systems, as well as the ecosystem (Brockmole and Wang, 2003). Consequently, a new space-time representation will consist of embedded contexts, which will not rely on similar reasoning backgrounds but will be derived from the integration of different inference modes (i.e. abduction, induction, and deduction).

However, in addition to capturing the contextual knowledge, it is fundamentally important that researchers explore the hypotheses (abstractions) to explain the interactions of complex patterns at the appropriate levels of detail. Approaches such as data mining make explicit this knowledge, so that by employing suitable inductive techniques, a computer system can perform operations for testing a hypothesis by experiment. Such an experiment consists in postulating that, if the hypothesis is true, a pattern observed under certain conditions (i.e. a context) ought to have certain types of micro as well as macro interactions. In other words, the experiment finds patterns in the observations in order to generate general hypotheses from the generalisation of the interactions and contextual knowledge. A space-time representation will play an important role in defining the boundaries and components of a complex system, and finally, in showing what principles really govern the self-organisation of complex networks.

In the near future, addressing the issues outlined from these three complementary perspectives will become research priorities. In moving forward, it is important to realise that no single discipline offers the necessary concepts, methodologies, and tools to develop a new space-time representation for framing the evolution of complex systems. We expect to see an increasing influence and prevalence of Mode 2 Science (i.e. science in the context of application rather than the context of discipline). This platform will encourage a cross-disciplinary scientific effort within which many scientists will engage in exploration by taking account of the application context of science after the initial analysis phases of scientific endeavour.

References

Arbib, M. A. (1995): *The handbook of brain theory and neural networks*. MA, MIT Press.

- Axelrod, R. M. (1997): *The complexity of cooperation: Agent-based models of competition and collaboration*. Princeton, NJ, Princeton University Press.
- Barabási, A.L. and Albert, R. (1999): "Emergence of scaling in random networks", *Science*, 286, 509. <http://arxiv.org/abs/cond-mat/9910332>.
- Batty, M. (2005): *Cities and complexity: Understanding cities with cellular automata, agent-based models, and fractals*. Cambridge, MA, MIT Press.
- Bédard, Y. and Bernier, E. (2002): "Supporting multiple representations with spatial view management and the concept of "VUEL"", *Proceedings of the Joint Workshop on Multi-Scale Representations of Spatial Data, ISPRS WG IV/3, ICA Communications on Map Generalization*. Ottawa, Canada.
- Brockmole, J. R. and Wang, R. F. (2005): "Spatial processing of environmental representations", in Itti, L., Rees, G. & Tsotsos, J. (Eds.): *Neurobiology of Attention*. San Diego, CA, Elsevier, pp. 146-152.
- Bruner, J. (1985): *Actual minds, possible worlds*. Cambridge, MA, Harvard University Press.
- Burrough, P.A. (1981): "Fractal dimensions of landscapes and other environmental data", *Nature*, 294, pp. 240-242.
- Cheyland, J. P. and Lardon, S. (1993): "Toward a conceptual model for the analysis of spatio-temporal processes", in Frank, A.U. and Campari, I. (Eds.): *Spatial Information Theory*. Berlin, Springer-Verlag, pp. 158-176.
- Chomicki, J. and Revesz, P.Z. (1999): "Constraint-based interoperability of spatiotemporal databases", *GeoInformatica*, 3, 3, pp. 211-243.
- Claramunt, C., Parent, C. and Theriault, M. (1997): "Design patterns for spatio-temporal processes", in Spaccapietra, S. and Maryanski, F. (Eds.): *Searching for Semantics: Data Mining, Reverse Engineering*. New York, Chapman & Hall, pp. 415-428.
- Epstein, J. M. (2007): *Generative social science: Studies in agent-based computational modelling*. NJ, Princeton, University Press.
- Forlizzi, L., Güting, R.H., Nardelli, E. and Schneider, M. (2000): "A data model and data structures for moving objects databases", *Proceedings of the ACM SIGMOD International Conference on Management of Data*. Dallas, Texas, USA.
- Frank, A. U. (1994): "Qualitative temporal reasoning in GIS - ordered time scales", *Proceedings of the Sixth International Symposium on Spatial Data Handling Conference*. Edinburgh, Scotland.
- Fry, B. (2007): *Visualizing Data*. Sebastopol, CA, O'Reilly Media Inc.
- Gilbert, G.N. (2008): *Agent-based models*. Los Angeles, Sage.
- Gilbert, N. and Troitzsch, K.G. (2005): *Simulation for the social scientist*. Maidenhead, UK, Open University Press.
- Grabher, G. (2006): "Trading routes, bypasses, and risky intersections: mapping the travels of 'networks' between economic sociology and economic geography", *Progress in Human Geography*, 30, 2, pp. 163-189.
- Griffiths, T., Fernandes, A.A.A., Paton, N.W., Mason, K., Huang, B., Worboys, M., Johnson, C. and Stell, J. (2001): "Tripod: A comprehensive system for the management of spatial and aspatial historical objects", *Proceedings 9th ACM Int. Symposium on advances in geographic information systems*. Atlanta, GA, USA.
- Haken, H. (1983): *Advanced synergetics: instability hierarchies of self-organizing systems and devices*. Berlin, Springer-Verlag.

- Hewings, G.J.D., Sonis, M., Boyce, D. (Eds.) (2001): *Trade, networks, and hierarchies: integrated approaches to modeling regional and interregional economies*. Heidelberg and New York, Springer-Verlag.
- Krzanowski, R. M. and Raper, J. (2001): *Spatial evolutionary modelling*. New York, Oxford University Press.
- Langran, G. (1992): *Time in geographic information system*. London, Taylor & Francis.
- Mainzer, K. (1996): *Thinking in complexity: the complex dynamics of matter, mind, and mankind*. New York, Springer.
- Mandelbrot, B.M. (1982): *The fractal geometry of nature*. New York, W.H. Freeman and Co.
- Manson, S.M. (2001): "Simplifying complexity: a review of complexity theory", *Geoforum*, 32, pp. 405-414.
- Montello, D. (1993): "Scale and multiple psychologies of space", in Frank, A.U. and Campari, I. (Eds.): *International Conference GIS – From Space to territory: The theories and methods of spatio-temporal reasoning*. Lecture Notes Computer Sciences 639, Springer Verlag, pp.136-152.
- Müller, J.C., Lagrange, J.P., Weibel, R. and Salgé, F. (1995): "Generalization: state of the art and issues", in Muller, J.C., Salge, J.P. and Weibel, R. (Eds.): *GIS and generalization: methodology and practice*. Taylor and Francis, pp. 3-7.
- Nellis, M.D. (2005): "Geospatial information technology, rural resource development, and future geographies", *Annals of the Association of American Geographers*, 95,1, pp.1- 10.
- Parent, C., Spaccapietra, S. and Zimanyi, E. (1999): "Spatio-temporal conceptual models: Data structure + space + time", *Proceedings of 7th ACM symposium on geographic information systems, GIS'99*. Kansas City, Missouri, USA.
- Peuquet, D.J. (2002): *Representations of space and time*. New York, Guilford Press.
- Piatti, B., Bär, H., Reuschel, A.K., Hurni, L. and Cartwright, W. (2009): "Mapping literature: towards a geography of fiction", *Cartography and Art*. Berlin and Heidelberg, Springer, pp. 177-192.
- Pfoser, D. and Tryfona, N. (1998): *Requirements, definitions and notations for spatio-temporal applications environments*. Chorochronos Tech. Report CH-98-09, November 1998.
- The Brain Technologies (2009): *The Brain. Visual information management*. Last accessed: 25 September 2009, <http://www.thebrain.com/#-50>.
- Timpf, S. (1998): *Hierarchical structures in map series*. Ph. D. thesis, Technical University of Vienna.
- Turnbull, B. (2007): "Maps narratives and trails: Performativity, hodology and distributed knowledges in complex adaptive systems - an approach to emergent mapping", *Geographical Research*, 45, 2, pp. 140-14.
- Van Vleck, C. (2007): *Information taking shape*. Last accessed: 25 September 2009. http://www.cvanvleck.com/vanvleck_thesis.html.
- Vieu, L. (1997): "Spatial representation and reasoning in artificial intelligence", in Stock, O. (Ed.): *Spatial and temporal reasoning*. Kluwer Academic Pub., pp. 5-41.
- Visual Complexity (2009): www.visualcomplexity.com. Last accessed: 1 October 2009.
- Von Neumann, J. (1966): *Theory of self-reproducing automata*. Champaign-Urbana, University of Illinois Press.
- Wachowicz, M. (1999): *Object-oriented design for temporal GIS*. Taylor and Francis.
- Weibel, R. and Dutton, G. (1999): "Generalizing spatial data and dealing with multiple representations", in Longley, P., Goodchild, M.F., Maguire, D.J. and Rhind, D.W. (Eds.):

Wachowicz, M. and Owens, J. B. (2009): "Space-time representations of complex networks: What is next?", *GeoFocus (Editorial)*, nº 9, p. 1-8. ISSN: 1578-5157

Geographical information systems: principles, techniques, management and applications. Geoinformation International, Vol. 1, 2nd edition.

Whitehead, A.N. (1925): *Science and the modern world.* New York, Macmillan.

Whitehead, A.N. (1929): *Process and reality: An essay in cosmology, Gifford Lectures delivered in the University of Edinburgh during the Session 1927-28.* London and New York, Macmillan.

Wiener, N. (1961): *Cybernetics: Or, control and communication in the animal and machine.* MA, MIT Press.

Wolfson, O. (2002): "Moving objects information management: The database challenge", *Proceedings 5th International Workshop on Next Generation Information Technologies and Systems.* Lecture Notes in Computer Science 2382. Heidelberg, Springer, pp.75-89.

Wong, D.W.S. and Fotheringham, A.S. (1990): "Urban systems as examples of bounded chaos: exploring the relationship between fractal dimension, rank size, and rural-to-urban migration", *Geografiska Annaler - Series B: Human Geography*, 72, 3, pp. 89-99.

Worboys, M. F. (1994): "A unified model of spatial and temporal information", *Computer Journal*, 37, 1, pp.26-34.