Graph-Theoretic Models for the Holistic Analysis of Actor-Networks with Emergent Properties

Alexey Tselykh1,* and Boris Denisov2
1Southern Federal University, 2 Chekhov Street, Taganrog, Russian Federation
2Green Oasis School, Tianmin, 4030 Shennan Middle Road, Futian District, Shenzhen, Guangdong, 518026, The People’s Republic of China

*Corresponding author

Abstract. This paper presents the results of a research in modeling a concept of a black box and a mechanism of translation in sociotechnical actor-networks with emergent properties based on the extended and powerful formalisms of hypergraphs, directed hypergraphs, hypernetworks, metagraphs, and nested metagraphs. We introduce graph-theoretical models that allow for systemic studies and holistic analysis of actor-networks using rich mathematical apparatus of a set theory. The main object of the research are actor-networks in Science and Technology Studies. We hope that our contribution to the arsenal of graphical presentation tools and rigorous mathematical models for actor-network analysis will encourage the transition from qualitative to quantitative studies and the wider practical application of actor-network theory.

Keywords: Actor-network theory; Science and technology studies; Metagraph, Socio-semantic network.

1. Introduction
The development of information and communication technologies has led to new ways of translating scientific knowledge, new types of scientific communications, and new models and methods of science study.

The actor-network theory (ANT) [1] that has been actively developing in sociology finds wide application in interdisciplinary Science and Technology Studies (STS) with a focus on the agentive role of non-human objects – scientific facts, theories, knowledge and practices, technical artifacts.

From the standpoint of ANT, a research paper as a material object is not only a text (a carrier of knowledge expressed in a character and symbol form), but a collective actant and center of a sociotechnical network producing scientific knowledge [2]. In this sense, it is an emergent result of the activity of a socially extended mind – a mind that is cognitively influenced by the tools and technologies used, as well as other systems of intelligence.

A critical analysis of research papers on modeling actor-networks has revealed the following attempts to express ANT in a graphic format: modeling fabrics of science using weighted random walks on multimodal hypergraphs [3]; a set of representations of a dynamic network in information security domain for analyzing the stability of an actor-network through a transformation trajectory in accordance with the Latour process model [4]; graphic syntax for representing the semantics of the structural model of an actor-network to study collective sociotechnical processes in information systems [5]; a full-matrix approach to the mapping of socio-semantic networks that shifts the focus from social actors and their semantics to a co-analysis of actors and topics on Twitter [6]. Further
research in this direction is also carried out in Bruno Latour’s medialab Science Po laboratory [7]. However, in most works, researchers do not reach the level of a formal presentation of elements and relationships but limit themselves to presenting elements and relationships in natural language. We argue that the graphical representation is more informative. By combining simplicity and visualization with the rich and developed mathematical apparatus of the theory of graphs and hypergraphs, the proposed models are designed to increase the number of quantitative studies in ANT and its wider practical application.

In this paper, we will search for an adequate mathematical and graphical model of a heterogeneous multiplex socio-semantic network that includes both human and non-human actants and multiple relationships between them. In this way we will analyze scientific creative work not in one plane, but in the logic of nodes “with as many dimensions as there are connections between actors” [1].

2. Research Methodology

2.1. Modeling Translation in Actor-Networks

In actor network theory, a translation is a concept that bridges the gap between the various aspects that are combined in technology. A translation involves the creation of convergence and homology, linking the things that were previously unlinked. Whereas there are countless objects and meanings in technology, a translation is the process linking these elements in a sociotechnical network. Any translation is the result of the work of heterogeneous intermediaries, or Träger. Through these translations, we trace the network. The object of ANT is a movement from one association to another, translations between intermediaries that generate traceable associations between heterogeneous elements – actants.

According to Latour, translation does not define a causal relationship but leads to the coexistence of two intermediaries. A translation is carried out when, due to the presence of some technical intermediary in the network, there are changes both in the ways of interaction between other actors and in casual relationships. Latour distinguishes between intermediaries and mediators: “An intermediary is what transports meaning or force without transformation.” [1] The concept of an intermediary covers diverse and heterogeneous materials, such as drawings, inscriptions and texts (technical reports, research papers, laws and regulations, stories, etc.) as well as software, contracts, and money. A mediator is something that spreads between actors and helps to better determine the relation between them. Mediators transform, translate, distort, and modify the meaning or the elements.

Choosing an adequate formalism for modeling a translation in actor-networks, we draw an analogy with RDF (Resource Description Framework), an abstract model for describing linked data that is used to represent statements about the resources of the Semantic Web. The basis of the RDF model is a three-part statement, or 3-tuple (triple) of the form (subject, predicate, object) called an RDF graph. In RDF graph, the subject is the source vertex (tail), the object is the target vertex (head), and the predicate is the arc directed from the subject to the object. Along with directed graphs, there are alternative representations and more powerful graph-theoretic formalisms: a labeled oriented graph, a bipartite graph, an undirected hypergraph, a directed hypergraph, and a metagraph.

An adequate formalism for describing the translation mechanism in an actor-network is a directed 3-uniform hypergraph, that is, a directed hypergraph without multiple edges, and every edge is a triple. Information about actants is stored in the vertices of a hypergraph. Directed hyperedge compactly and naturally represents the role of each vertex, as well as the direction of the translation. Note that this approach requires less memory to store data than other representations $|V| = |\text{unlabeled}(T)|$, $|E| = |T|$. We can also consider the formalism of a type-2 directed hypergraph [8], which is a generalization of the concept of a directed graph from the position of dividing the set of vertices that form the edges into groups of the “beginning” and the “end” of the edge. In the edge of type-2 directed hypergraph, some vertices (at least one) can be marked with the index “*”, and at least one of the vertices is not marked with this index. For a hypergraph $H = (X, U)$, each edge $u_j \in U$ can be represented as a directed bipartite graph $G(U) = (X_j \cup X_j', \Gamma, \Gamma')$, where $X_j$ is the set of unlabeled vertices of the edge $u_j$, $X_j'$ is the set of labeled vertices of the edge $u_j$, and $\Gamma, \Gamma'$ are the mappings given for all unlabeled and
labeled vertices, respectively. In the context of ANT, the labeled vertex is an intermediary in a translation. Note that to study the properties of these graph formalisms, one can use the powerful informative and formal apparatus of ultragraphs.

2.2. Modeling the Concept of a Black Box in Actor-Networks

The concept of a black box in ANT is used to determine the set of well-established and sufficient relations between actors. Latour defines a black box as a set of elements that are already assembled and acting as a whole, and we are not very interested in the nature of what is collected, connected and packaged together. A black box emerges when many elements work as one and so predictable that we do not need to know the principle of their assembly. An example of a black box is a significant discovery (invention, idea) that is scattered in public practice. The emergence of the black box is equivalent to the emergence of a new functional unit, which receives a new name, with qualitatively new, emergent properties. For example, a seat belt in an airplane, or nuclear weapons can be considered complex black boxes that depend on methods, materials, thought processes and behavior. The opening of the black box of technologies leads to a study of how the various social aspects and technical elements are connected as a whole.

In a search for ways to model a black box, we consider the concept of association from the theory of connectomics, an area of research on brain activity, dedicated to modeling the entire set of connections between neurons in the nervous system – the connectome, by analogy with genome.

The ideas of connectionists were developed in the works of K. Anokhin on hypernetwork brain theory [9]. According to Anokhin, the mind has a granular structure, it consists of COGs – distributed groups of neurons linked by common cognitive experience and forming stable connections – LOCs. COGs and LOCs form a network – cognitome. A set of connected elements of the lower level network (neuronal ensemble) corresponds to an element of the upper level (COG).

Anokhin refers to the mathematical apparatus of hypernetworks [10] which allows modeling structures that are more complex than networks, graphs, and hypergraphs. In terms of algebraic topology, COG is a relational simplex, or hypersimplex, which can be graphically represented as a sheaf. The base of a hypersimplex contains a set of elements of one level, and its vertex is formed by a description of their relationships and acquires integral properties that make it an element of a higher-level network – a hypernetwork. A structured set of elements is called relational because the relations are explicitly defined. The vertex of the COG receives a name corresponding to the cognitive information carried by the COG. According to Anokhin, hypernetworks are not just a synthesis of various representations of a network science but represent a qualitatively new theory that adequately reflects emergence phenomena in multilevel systems.

By drawing obvious parallels, an actor-network can be described as a complex network with emergent properties – such a network in which a single fragment consisting of vertices and relations can act as a separate whole. In terms of the theory of hypernetworks, a black box in an actor network is a hypersimplex, the real assembly at the base of which is mapped to the vertex of a higher level using the assembly relation function. Due to the emergence of hypersimplexes during the transition between levels, a systemic property of emergence holds. The bases of hypersimplexes can intersect, inducing connectivity and lattice structures (e.g. Galois lattices). Multilevel systems may contain compositions of relationships.

However, for our task, the formalism of a hypernetwork has several significant limitations. First, it does not allow us to fully describe the agentivity of a black box. Second, the edges at the base of a simple hypernetwork do not have orientation that is required to formalize the relation of translation in an actor-network.

These restrictions should be removed in a desired hierarchical graph-hypergraph model, allowing for various levels of generalization, including but not limited to:

- Representation of multiple heterogeneous relationships in the form of a hierarchy of graphs within one subset (inside the edge of a hypergraph).
- Representation of multiple heterogeneous relationships in the form of graphs between elements of different subsets included in different edges of a hypergraph. In practice, such a hypergraph is represented by two layers of relations on the same set of vertices. The first layer is represented by
hypergraph edges, and the second by graph edges. For example, scientific schools and citations. Representation of relations between subsets (edges of a hypergraph). For example, the connection between the hyperedges can indicate the dependence of one subject area on another. A full spectrum of relations was considered by us earlier in [11].

Further, we consider a metagraph model. Metagraph $MG$ can be defined as follows: $MG = (V, MV, E)$, where $V$ is the set of vertices, $E$ is the set of edges defined on the set $V$; $MV$ is the set of metavertices defined on the set $V \cup MV \cup E$.

In other words, whilst a hyperedge of a hypergraph can only include vertices, a metavertex of a metagraph can include both vertices (or metavertices) and edges. An edge in a metagraph can connect vertices within a single metavertex, vertices between different metavertices, metavertices, as well as vertices and metavertices.

In [12], along with the concept of a metagraph, the concept of a nested metagraph (an n-level graph) is introduced as a generalization of graphs, hypergraphs, and metagraphs.

A nested metagraph allows the orientation of edges. A nested metagraph of level 2 is an ordered pair $G = (X, E)$, where $X = \{x_i\}_i \in \mathbb{I}, \mathbb{Z}$ is a finite nonempty set of vertices, $f_i: g_i(x_i, e_i) \to x_i^P$ is the assembly function, $E = \{e_k\}$ is a set of edges of the graph, where $k = \mathbb{I}, \mathbb{m}$, i.e. each edge of the graph connects two subsets of the set of vertices. A nested metagraph of level 2, which has at least one edge between the vertices of the second level, is a metagraph. A nested metagraph of level 2, which has no edges between the vertices of the second level, is a hypergraph.

A nested metagraph of level 3 is an ordered pair $G = (X, E)$, where $X = \{x_i\}_i \in \mathbb{I}, \mathbb{Z}$ is a finite nonempty set of vertices, and the assembly function is defined as $f_i: g_i(x_i, e_i) \to x_i^P$, $f_i^P: g_i^P(x_i^P, e_i^P) \to x_i^P$; $E = \{e_k\}$, $k = \mathbb{I}, \mathbb{m}$. In the general case, vertices $x_i^P$ are edges in graphs $g_i(x_i, e_i)$, and vertices $x_i^P$ are hyperedges in hypergraphs $g_i^P(x_i^P, e_i^P)$.

Figure 1. Modeling actor-network by a nested metagraph of level 3.
Hypersimplex as a combination of elements of different levels can be represented as a metavertex. In fact, metagraphs and hypernetworks are just different formal descriptions of the same processes that occur in networks with emergent properties.

In the nested metagraph in Fig. 1, the actant $a_3 \in X$ acts as an intermediary in the relation of translation, which is represented by the directed hyperedge $t_2 \in E$. The same actant takes a different role in the translation $t_1$. Translations may not have common vertices $t_3 \cap (t_1 \cup t_2) = \emptyset$. A subset of translations packed into a black box forms a hypersimplex (metavertex $bb_1$). The edge of the metagraph connects vertex $a_{11}$ and metavertex $bb_1$ in translation $t_5$.

3. Conclusion
A directed hyperedge compactly and naturally represents the role of each vertex, as well as the direction of translation in actor-networks. The emergence property for the black box holds due to the emergence of hypersimplexes in the transition between levels using the assembly function. The systemic, holistic model of a nested metagraph allows connections both between elements of the same level, and between elements of different levels so the black box can become an actant in an actor-network.

Our findings provide a scientific basis for studying the structural properties of actor-networks from the standpoint of set theory using well-known algorithms on graphs and hypergraphs.

Acknowledgement
This work was supported by the grant of Russian Foundation for Basic Research, project No. 17-01-00243.

References
[1] B. Latour, Reassembling the Social: An Introduction to Actor-Network-Theory, Oxford University Press, New York, 2005.
[2] N.G. Popova, Research Paper as the Core of a Socio-technical Knowledge Generation Network, Sociology of Science and Technology. 1 (2017) 68-84.
[3] F. Shi, J.G. Foster, J.A. Evans. Weaving the fabric of science: Dynamic network models of science's unfolding structure, Social Networks. 43 (2015) 73-85.
[4] A. Tsohou, M. Karyda, S. Kokolakis, E. Kiountouzis, Analyzing trajectories of information security awareness, Information Technology & People. 25, 3 (2012) 327-352.
[5] E. Silvis, P. Alexander, A study using a graphical syntax for actor-network theory, Information Technology & People, 27, 2 (2014) 110-128.
[6] I. Helsten, L. Leyesdorff, Automated Analysis of Topic-Actor Networks on Twitter: New approach to the analysis of socio-semantic networks. November 2017. arXiv:1711.08387.
[7] T. Venturini, D. Guido, Once upon a text: an ANT tale in Text Analytics, Sociologica. 3 (2012) 1-17.
[8] L.S. Bershtein, Nechetkie grapy i gipergrapy, Nauchnyi mir, Moscow, 2005.
[9] K. Anokhin, Cognitome: the theory of neural hypernetwork, In Proceedings of the Workshops on Critical and Collective Effects in Graphs and Networks (CCEGN 2019), Les Houches, France (2019)
[10] J.H. Johnson, Hypernetworks for reconstructing the dynamics of multilevel systems, In Proceedings of European Conference on Complex Systems (ECCS’06), Oxford, UK (2006)
[11] N.E. Sergeev, A.A. Tselykh, A.N. Tselykh, Generalized approach to modeling user activity graphs for network security and public safety monitoring, In Proceedings of the 6th International Conference on Security of Information and Networks (2013) 117-122.
[12] S.V. Astanin, N.V. Dragynsh, N.K. Jukovskaya, Vlojennye metagrafy kak modeli slojnyh ob’ektov, Injenernyi vestnik Dona. 23, 4-2 (2012)