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The Language of Networks

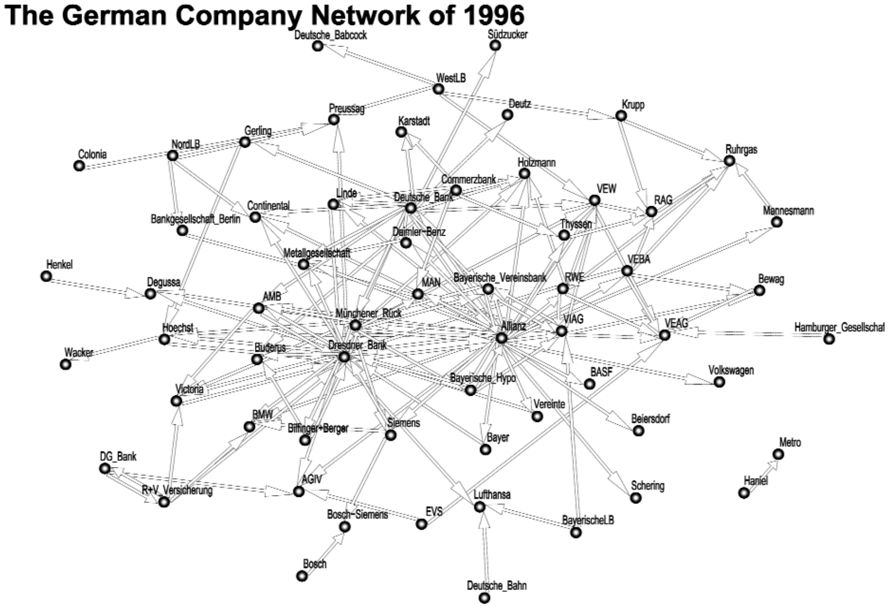
Network-Linked Worlds

Complex networks have become an important topic of discussion in many scientific disciplines today. Understanding the interaction of numerous linked entities and the resulting dynamics is a tremendous scientific challenge.
Internationalization and globalization are advancing in many areas. New information technologies span tremendous distances in seconds. In only a few years, the Internet has made major inroads into our lives. Today, knowledge is available and retrievable online globally and in unprecedented diversity.
Globalization also means an accelerating integration and interconnection of national economies through the increasing flows of goods, investments and capital across historical borders. This is accompanied by transfers of organizational capabilities, technologies, ideas, information, entertainment and culture.
Network researchers are not the only ones who see the traditional sciences as being on the verge of a paradigm shift. The characteristics of complex systems and how they function are now coming to the fore in biology and physics as well. Whereas 20th-century scientists strove to identify elementary units (like atoms and cells) and to work out their properties, it has become apparent that it is impossible with this knowledge alone to understand the interaction of large numbers of these units. The attempt to assemble elements with known characteristics into stable systems runs up against the limits of complexity as the quantity of possible arrangements quickly exceeds the limits of calculability (see Barabasi, 2002).
Thus, the point is to understand which forms of network linkage are applicable to the performance capabilities of complex systems. How does the structure of networks correlate with their stability? Which modifications can permanently impair networks and which cannot? The investigation of networks promises to deliver answers to a great many questions. Under what conditions are ecosystems stable? When do interventions in nature disturb the stability of systems that provide us with the food we eat? How can medicines treat problems in complicated metabolic processes without side effects? What are the functional limits of public utility and transportation infrastructure (water, electricity, transit/traffic networks)? How is international integration progressing? How is digital communication changing our everyday life and social relationships?

Networks and Visualization

Analyzing a network requires as a rule the processing of very large quantities of information describing the interrelationship of the elements that comprise the network. Extensive calculations are performed on this data, so that it has only been the availability of computers that has made it possible to automatically analyze large networks.
Since the very inception of this approach, investigations of networks have continually been accompanied by attempts to depict them graphically (see Freeman, 1999). Although the first hand-drawn sketches merely showed connections between more or less randomly ordered persons (see Moreno, 1953), a degree of interpretive skill applied to such graphics did indeed facilitate understanding certain characteristics of the networks portrayed. Today, the depiction of networks is a combination of various steps, each of which solves a specific part of the problem. The crux of this matter is how units of interconnected systems can be represented spatially in relation to one another.

Even classical metric statistics had variously substantiated procedures at its disposal by means of which linkages between a large number of entities could be depicted spatially. Factor analysis, correspondence analysis as well as processes of metric and non-metric scaling enable us to apply various assumptions to linkage data (weighted linkages or distances) in order to generate spatial arrangements (i.e. to ascertain the positioning of the described entities). These are more or less suitable to produce global landscapes of the units described by the data. The solutions place objects in statistical spaces and result in landscapes in which proximity in space corresponds to the strength of the observed linkage. Entities linked up in networks are typically represented as points or rings of a certain magnitude and linkages as lines of a certain thickness.
In contrast to geographical maps, physical proximity in networks is defined by functional references: who is especially strongly connected to whom, or who is connected in the same way to whom. The ordered network landscapes describe spheres of influence, potential scopes of action and contexts of effect in which certain entities are significant for other entities. Their significance varies with the type of entities (i.e. social protagonists or technical devices) and the type of relationships (i.e. friendship, contact, communication, cooperation, exchange, commerce or the transference of information, energy flows or food chains).



Equity Interrelationships among the 100 largest German companies, 1996

Today, one would be likelier to use algorithms that make it possible to flexibly order networks. Apparently, nonlinear solutions are particularly easy for people to grasp in this way, even if no universal scale for the distance between units exists in such arrangements. In these representations, the locally coherent concentrations (neighborhoods) of linear arrays remain intact—large intervals are shrunk and, conversely, very small intervals are enlarged. They are simplified arrangements of network-linked units.
It is astounding that many of these diagrams can often be read very easily. They provide orientation similarly to the way maps do. The fascinating thing about these charts is that

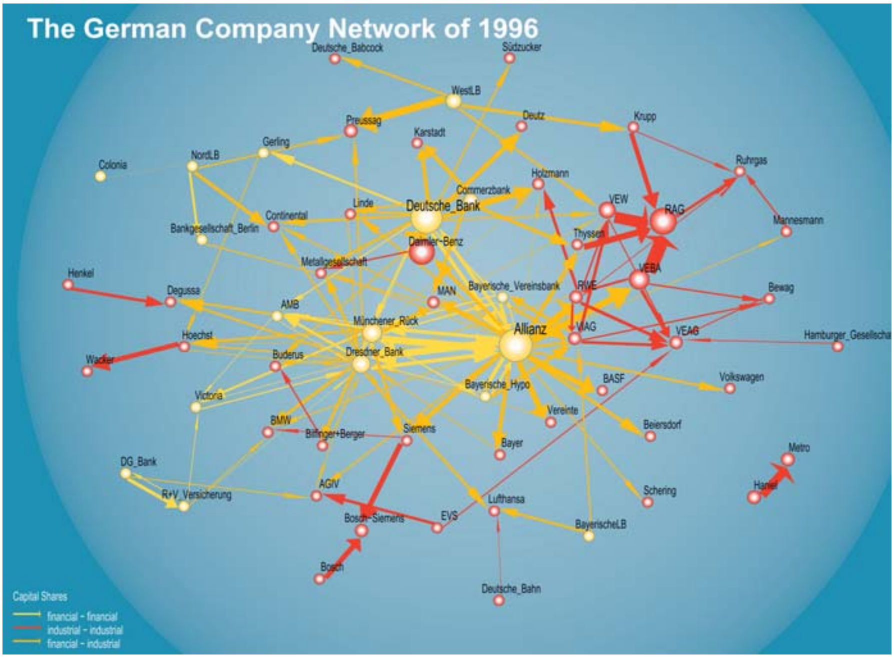
they fit together a multitude of observations like pieces of a jigsaw puzzle into a picture of the system as a whole. The human eye can discover particular patterns in them with relative ease.

Network-linked systems often consist of subsystems that are more or less strongly interconnected. Agents that link up subsystems assume important positions. Within subsystems, agents are locally central when they exhibit direct connections there. Whatever networks describe—whether technical infrastructures like streets or telephone networks, social groups, corporations, institutions or nations—their arrangement in the pictorial representation identifies neighborhoods and provides information about the situation and the closeness of the relationship among the entities linked up in those networks.

In highly structured networks in which many subsystems are only weakly linked to each other, entities that control many of the shortest linkages between other network participants gain potential power and assume importance. They occupy strategic positions since they control the exchange among many entities and can interrupt the flow of information.

A second type of picture emerges when the effort is made to depict special qualities of networks, their component entities or certain subsystems in the form of additional graphic features. This necessitates the use of additional graphic attributes: sizes, colors or forms that graphically ascribe these characteristics to the layout of the network. In doing so, graphical-theoretical qualities derived from the linkages are integrated into the depiction and can thus be read simultaneously.

If the centrality of the particular entities is portrayed by means of the size of the symbols, then a reading of the graphic representation provides additional information about who is involved in an especially large number of relationships (degree), who can reach many agents via particularly short paths (closeness) and who controls an especially large number of the shortest linkages to an adjacent network (betweenness).



The network of equity interrelationships with sizes and color markings

Since human perception reacts especially sensitively to symbols' size, what emerges in the picture is a second set of (partially redundant) information. This enables viewers to get oriented faster, as the size of the symbols directs their attention.
A third class of "analytical graphics" emerges if, in similar fashion, external information about the component units or their interrelationships (e.g. theoretical classifications or independently gathered data) is introduced into the representation.
In an analysis of equity capital interrelationships, for example, classifying firms as industrial enterprises, banks and insurance companies, and selecting a different color for each category makes it easy to recognize particular concentrations in the network—areas displaying a preponderance of units of the same color indicate internal interrelationships. These can be examined more closely by means of lines in a derivative color scheme: the extent to which such investments are held exclusively among banks and industrial enterprises or whether the majority of the interrelationships consists of equity capital interpenetration by banks and industrial enterprises.
In this case, utilizing different colors projects a theoretically significant classification onto the arrangement of a network. The depiction makes it possible to ascertain whether the theoretical process of differentiation exhibits systematic patterns in the optimized arrangement of the network. In contrast to a purely statistical treatment, weak local interconnections also emerge in networks. They indicate the structure's potential for development.

Visual Statistics

The potential of such "visual statistics" is strongly dependent upon a series of additional questions. How can quantitative information be communicated? In what cases can depictions of manifold information be interpreted especially easily and quickly?
French cartographer Jacques Bertin already provided an important key to understanding such fundamental problems of information processing in his 1974 work "The Semiology of Graphics." What distinguishes visual symbols from other systems of signs (writing, language and music) is their capability of simultaneously communicating different types of information. Converting numerical information is a process of translation into elementary graphic signs. With the elementary graphic attributes of size, color and form, multiple sets of information can be communicated independently of each other and simultaneously. If the natural categories of human perception are exploited in doing this, then the translation is especially effective.
In order for the information described in the measurements of a network to be systematically translated into standardized sense impressions, however, there must be certain rules of graphic representation (see Krempel 2004) that guarantee that, through the variation of graphic signs, the information is translated into corresponding sense impressions. They assure that a user can derive the same information from an image as from the figures of numerical measurements.
It is astounding to note that these very same questions have been investigated for over 100 years in the field of psychophysics, which deals with how certain stimuli (sizes, lengths, colors) have to be varied in order to trigger identical sensory perceptions on the part of a viewer. Through the application of functions identified in this research, information can be translated in such a way that the orderings of the information also take shape visually in the observer's mind.
Indeed, the communication of orderings by means of colors is a much more complex undertaking. Although researchers have long been aware of many perception-oriented color systems that differentiate colors according to tone, brightness and saturation, these systems nevertheless do not describe uniformly perceived gradations. Today's psychometric color

systems have—unbeknownst to many—already gained entry into our everyday life. In 1976 they were introduced as international standards (CIE l*ab*). They are the results of both decades of quantification by an ambitious group of colormetricians as well as of the identification of mathematical functions by means of which the psychometric Munsell System can be applied to the physical model of colors.

A Graphic Scientific Language

If relational observations are ordered according to systematic rules and additional external information is pictorially projected into these orderings in a way that takes psychophysiological principles into consideration, then the results are highly optimized graphical information landscapes, artificial worlds that fit together manifold descriptions of the same objects and reconstruct these objects according to systematic rules. This makes it possible to inspect local, multidimensional patterns and to study the positioning within the system as a whole of the elements that have been multiply described in this way.

The use of colors in particular expands the possibilities of discovering within these structures concentrations of characteristics that identify multivariant linkages. The technologies for automatically generating colors as well as the capability of utilizing different technologies to evoke similar color impressions on the part of different people are based upon an enormously improved understanding of the human perception of color. Although the use of these color technologies has quickly become very widespread in our everyday life, the scientific use of colors in the investigation of complex issues is still pretty much in its formative phase.

The extent to which we are able to better understand and apply these rules will determine how well we can take advantage of the natural attributes of human perception for scientific purposes. In going about this, ergonomically optimized graphics use the particular capabilities of human perception for scientific purposes in a systematic way. This makes it possible to join together the potential of automatic procedures with the special capacities of human perception.

Although the visualization of networks is barely out of its infancy, it promises to provide insights into very complicated processes and to make new worlds visible.

Translated from German by Mel Greenwald

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