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An information-theoretic framework for resolving community structure in complex networks

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To understand the structure of a large-scale biological, social, or technological network, it can be helpful to decompose the network into smaller subunits or modules. In this article, we develop an information-theoretic foundation for the concept of modularity in networks. We identify the modules of which the network is composed by finding an optimal compression of its topology, capitalizing on regularities in its structure. We explain the advantages of this approach and illustrate them by partitioning a number of real-world and model networks.

clustering | compression | information theory

Many objects in nature, from proteins to humans, interact in groups that compose social (1), technological (2), or biological systems (3). The groups form a distinct intermediate level between the microscopic and macroscopic descriptions of the system, and group structure may often be coupled to aspects of system function including robustness (3) and stability (4). When we map the interactions among components of a complex system to a network with nodes connected by links, these groups of interacting objects form highly connected modules that are only weakly connected to one other. We can therefore comprehend the structure of a dauntingly complex network by identifying the modules or communities of which it is composed (5–10). When we describe a network as a set of interconnected modules, we are highlighting certain regularities of the network's structure while filtering out the relatively unimportant details. Thus, a modular description of a network can be viewed as a lossy compression of that network's topology, and the problem of community identification as a problem of finding an efficient compression of the structure.

This view suggests that we can approach the challenge of identifying the community structure of a complex network as a fundamental problem in information theory (11–13). We provide the groundwork for an information-theoretic approach to community detection and explore the advantages of this approach relative to other methods for community detection.

Fig. 1 illustrates our basic framework for identifying communities. We envision the process of describing a complex network by a simplified summary of its module structure as a communication process. The link structure of a complex network is a random variable X ; a signaler knows the full form of the network X and aims to convey much of this information in a reduced fashion to a signal receiver. To do so, the signaler encodes information about X as some simplified description Y . She sends the encoded message through a noiseless communication channel. The signal receiver observes the message Y and then “decodes” this message, using it to make guesses Z about the structure of the original network X .

There are many different ways to describe a network X by a simpler description Y . Which of these is best? The answer to this question of course depends on what you want to do with the description. Nonetheless, information theory offers an appealing general answer to this question. Given some set of candidate descriptions Y_i , the best description Y of a random variable X is the one that tells the most about X ; that is, the one that

maximizes the mutual information $I(X;Y)$ between description and network.

Since we are interested in identifying community structure, we will explore descriptions Y that summarize the structure of a network X by enumerating the communities or modules within X and describing the relations among them. In this article, we will consider one particular method of encoding the community structure of X . More generally one could and indeed should consider alternative “encoders,” so as to choose one best suited for the problem at hand.

We consider an unweighted and undirected network X of size n with l links, which can be described by the adjacency matrix

$$A_{ij} = \begin{cases} 1 & \text{if there is a link between nodes } i \text{ and } j \\ 0 & \text{otherwise} \end{cases} \quad [1]$$

We choose the description

$$Y = \left\{ \mathbf{a} = \begin{pmatrix} a_1 \\ \vdots \\ a_n \end{pmatrix}, \mathbf{M} = \begin{pmatrix} l_{11} & \cdots & l_{1m} \\ \vdots & \ddots & \vdots \\ l_{m1} & \cdots & l_{mm} \end{pmatrix} \right\} \quad [2]$$

for m modules, where \mathbf{a} is the module assignment vector, $a_i \in \{1, 2, \dots, m\}$, and \mathbf{M} is the module matrix. The module matrix $\mathbf{M} = \mathbf{M}(X, \mathbf{a})$ describes how the m modules given by the assignment vector are connected in the actual network. Module i has n_i nodes and connects to module j with l_{ij} links (see Fig. 1).

To find the best assignment \mathbf{a}^* , we now maximize the mutual information over all possible assignments of the nodes into m modules

$$\mathbf{a}^* = \arg \max_{\mathbf{a}} I(X;Y). \quad [3]$$

By definition, the mutual information $I(X;Y) = H(X) - H(X|Y) = H(X) - H(Z)$, where $H(X)$ is the information necessary to describe X , and the conditional information $H(X|Y) = H(Z)$ is the information necessary to describe X given Y (see Fig. 1). We therefore seek to minimize $H(Z)$. This is equivalent to constructing an assignment vector such that the set of network estimates Z in Fig. 1 is as small as possible. Given that the description Y assigns nodes to m modules,

$$H(Z) = \log \left[\prod_{i=1}^m \binom{n_i(n_i-1)/2}{l_{ii}} \prod_{i>j} \binom{n_i n_j}{l_{ij}} \right], \quad [4]$$

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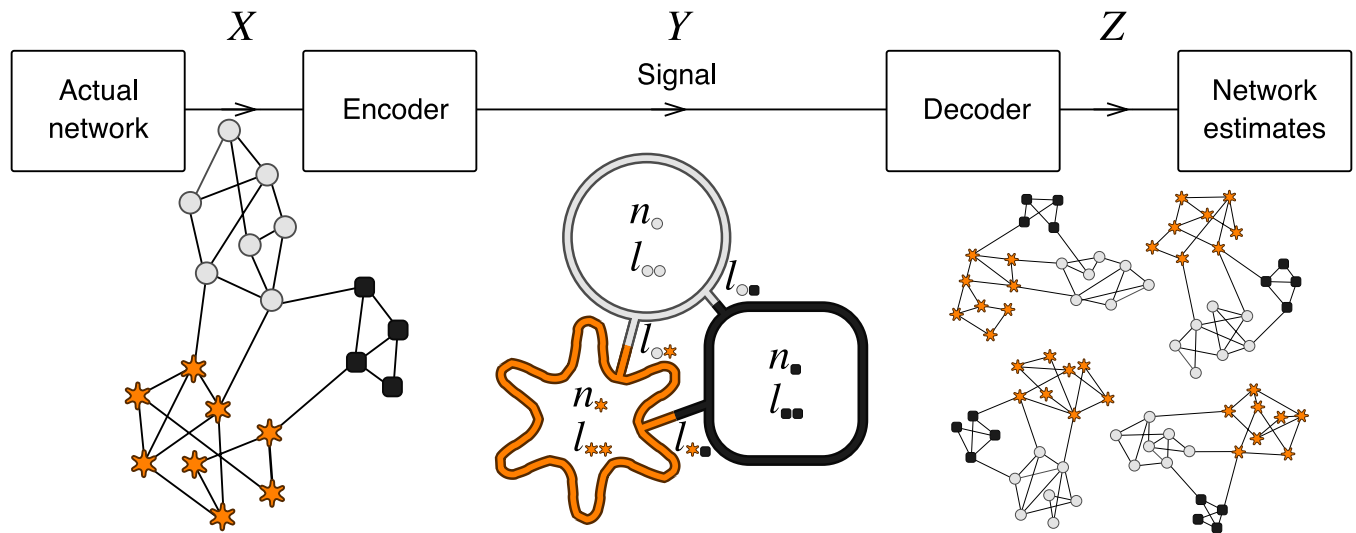


Fig. 1. Basic framework for detecting communities as a communication process. A signaler knows the full network structure and wants to send as much information as possible about the network to a receiver over a channel with limited capacity. The signaler therefore encodes the network into modules in a way that maximizes the amount of information about the original network. This figure illustrates an encoder that compresses the network into three modules, $i = \text{circle, square, star}$, with n_i nodes and l_{ij} links connected by l_{ij} links between the modules. The receiver can then decode the message and construct a set of possible candidates for the original network. The smaller the set of candidates, the more information the signaler has managed to transfer.

where the parentheses denote the binomial coefficients and the logarithm is taken in base 2. Each of the m binomial coefficients in the first product gives the number of different modules that can be constructed with n_i nodes and l_{ii} links. Each of the $m(m-1)/2$ binomial coefficients in the second product gives the number of different ways module i and j can be connected to one another.

In Fig. 2, we apply our cluster-based compression method to the dolphin social network reported by Lusseau *et al.* (14). Our method selects a division that differs by only one node from the division along which the actual dolphin groups were observed to split. Because it is computationally infeasible to check all possible partitions of even modestly sized networks, we use simulated annealing with the heat-bath algorithm to search for the partition that maximizes the mutual information between the description and the original network. We have confirmed the

results for the networks in the figures with exhaustive searches in the vicinity of the Monte Carlo solutions.

We compare our results with the partition obtained by using the modularity approach introduced by Newman and Girvan in ref. 15; that technique has been widely adopted because of its appealing simplicity, its performance in benchmark tests (10), and the availability of powerful numerical techniques for dealing with large networks (16–18). Given a partitioning into m modules, the modularity Q is the sum of the contributions from each module i

$$Q = \sum_{i=1}^m l_{ii}/l - (d_i/2l)^2, \quad [5]$$

where l_{ii} is the number of links between nodes in the i th module, d_i is the total degree in module i , and l is the total number of links

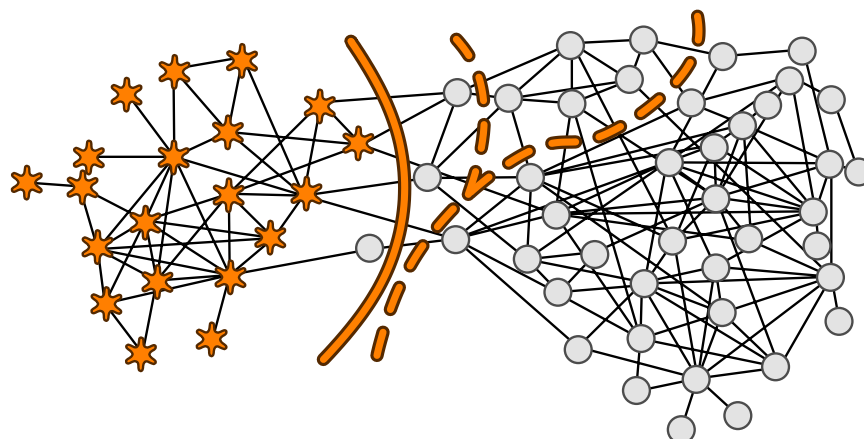


Fig. 2. The dolphin network of Lusseau *et al.* (14) partitioned with our cluster-based compression (solid line) and based on the modularity (dashed line). The right branch of the dashed line represents a split based on maximizing the modularity, which is different from the left branch solution based on the spectral analysis approximation presented in ref. 31. The edge-betweenness algorithm presented in ref. 5 splits the network in the same way as our cluster-based compression method (15).

a module is (26, 27), we might be interested only in those clusters with more links within than between clusters ($l_{ii} > l_{ij}$ for all i and j in Eq. 2). However, choosing modules in that way will not necessarily maximize mutual information. In many cases, we get a higher mutual information by selecting modules such that hubs are clustered together and peripheral nodes are clustered together. When this is true, we can describe the network structure more efficiently by clustering nodes with similar roles instead of clustering nodes that are closely connected to one another. The mixture model approach provides an alternative method of identifying aspects of network structure beyond positive assortment (28). In our examples where we want to find modules with more links within modules than between them, we impose a “link constraint,” penalizing solutions with more links between than within in the simulated annealing scheme.

To visualize the different ways of partitioning a network, we split Zachary’s classic karate club network (29) with (Fig. 4A) and without (Fig. 4B) the link constraint. In Fig. 4A, the partitioning corresponds exactly to the empirical outcome that was observed by Zachary. However, in Fig. 4B, the five members with the highest degrees are clustered together. In the first case, the compression capitalizes on the high frequency of ties between members of the same subgroup and the relatively few connections between the groups. In the second case, the compression takes advantage of the very high number of links between the five largest hubs and the peripheral members, and the very few connections between the peripheral members. The compression with the hubs in one cluster and the peripheral nodes in the other cluster is in this case more efficient.

We have shown that the process of resolving community structure in complex networks can be viewed as a problem in data compression. By drawing out the relationship between module detection and optimal coding, we are able to ground the concept of network modularity in the rigorous formalism provided by information theory.

Enumerating the modules in a network is an act of description; there is an inevitable tradeoff between capturing most of the network structure at the expense of needing a long description with many modules and omitting some aspects of network structure so as to allow a shorter description with fewer modules. Our information-theoretic approach suggests that there is a

natural scale on which to describe the network, thereby balancing this tradeoff between under- and over-description.

The main purpose of this article is to propose a new theoretical approach to community detection, and thus we have not extensively explored methods of optimizing the computational search procedure. Nonetheless, we have partitioned networks of sizes up to 10^4 nodes with a simple simulated annealing approach. While many interesting real-world networks are smaller than this, it is our hope that the approach can be used for even larger networks with other optimization methods such as the greedy search technique presented in ref. 30.

For many networks, our cluster-based compression method yields somewhat different results than does the modularity approach developed by Newman and colleagues. The differences reflect alternative perspectives on what community structure might be. If one views community structure as statistical deviation from the null model in which the degree sequence is held constant but links are otherwise equiprobable among all nodes, then the modularity optimization method by definition provides the optimal partitioning. If one views community structure as the regularities in a network’s topology that allow the greatest compression of the network’s structure, then our approach provides a useful partitioning. The choice of which to pursue will depend on the questions that a researcher wishes to ask.

In this article, we have concentrated on finding communities of nodes that are positively clustered by the links among them. While this is a common goal in community detection, the sort of information that we wish to extract about network topology may vary from application to application. By choosing an appropriate encoder, one can identify other aspects of structure, such as the hub versus periphery distinction illustrated in our alternative partitioning of the karate club network. When we abstract the problem of finding pattern in networks to a problem of data compression, the information-theoretic view described here provides a general basis for how to get the most information out of a network structure.

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