# Milieu and Function: Toward a Multilayer Framework for Understanding Social Networks

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**Abstract.** Social interactions between individuals do not occur in a void. Nor do they take place on a pre-existing fixed social network. Real social behaviour can be understood both to take place on, and to bring about, a complex set of overlapping topologies best described by a multilayer network in which different layers indicate different modes of interaction. Here we distinguish between the milieu within which social organisation is embedded and the transactional relationships that constitute this social organisation. While both can be represented by network structures, their topologies will not necessarily be the same. Researchers in various domains have realised the importance of the context in which individuals are embedded in shaping properties of the functional transactions in which they choose to engage. We review several examples of the relationship between milieu and function and propose a conceptual framework that may help advance our understanding of how social organisation can occur as a result of self-organisation and adaptation.

## 1 Introduction

An important challenge for understanding social behaviour is to understand the conditions conducive to its emergence. This challenge can be expressed by the pair of questions: What are the organisational structures that support the existence of social behaviour? and conversely, to what organisational structures does social behaviour give rise?

In the domain of one type of social behaviour, cooperation, advances have been made toward understanding how the structure of interactions can enable individuals to suppress self-interest and act in a cooperative fashion. An individual is more likely to interact cooperatively with another if it thinks they are likely to engage in future interactions [1]. The emergence of cooperative social behaviour is therefore more likely if individual interactions are determined to some extent by a persistent population structure [2]. In some models, persistent patterns of interaction are achieved by embedding a population in a spatial domain [3]. More recent studies have explored the situation in which interaction structure is represented by a network, where nodes are individuals and links indicate the subset of the population with which a particular individual can interact [4–7]. One finding of these studies is that the topology of the interaction network can affect the likelihood of cooperation occurring [6].

One topological feature that has been associated with the appearance of cooperation is the presence of community structure [8]. A community is a subset of individuals that have more links to other members of the community than to individuals from the remainder of the network. Communities consisting primarily of like-minded individuals may support the emergence of cooperation, by providing an environment in which co-operators are more likely to interact with other co-operators and less likely to be exploited by defectors [9]. Whereas spatial constraints on interaction are an external enabling factor with regard to cooperation, community structure and cooperation are more inextricably bound: communities *are* social behaviour.

A limitation of many existing network models of social behaviour is that links represent only a single type of interaction, such as friendship, trading or communication. By contrast, real individuals engage concurrently in a rich variety of different modes of interaction. The sets of individuals with which they interact may differ depending on the mode of interaction. For example, a diplomat may engage in negotiations with one set of colleagues, but socialise with another, perhaps partially overlapping set of acquaintances. So, the structure of a population is not defined by a single unimodal network, but rather by a network consisting of many overlapping layers, each with their own mode of interaction [10]. The potential for coupling and feedback between the layers of such networks is largely unexplored. Furthermore, by conflating interaction and its context into a single network topology, it is difficult to address the question of how social behaviour emerges, as the existence of sociality is already presupposed.

While most models of social systems have used unimodal networks, the importance of context for understanding functional behaviour has been recognised across a wide range of domains. Our first aim in this paper is to review this literature and draw together the disparate examples of multivariate networks. Our second aim is to move from these concrete examples toward a unifying conceptual framework. Our final aim is to outline some of the directions in which we feel future progress can be made.

## 2 Multiple Modes of Interaction

The fact that individuals tend to be simultaneously engaged in multiple modes of interaction has received little explicit attention from the modelling community. However, the embeddedness of functional interactions within a social or environmental context is a topic of interest in numerous domains, several of which we review below.

**Transportation:** Transportation networks consist of locations and journeys rather than individuals and interactions. However, they warrant mention both as a clear and concrete example of a multilayer network, and because they are one of the few networks to have been explicitly analysed as such [11].

In transportation networks, a distinction can be drawn between the physical infrastructure–the roads and rail tracks on which travel occurs–and the logical

network of journeys, in which links join a journey's source to its destination, irrespective of the intervening route. Making this distinction reveals that these two networks have very different topologies [11]. It has been suggested that these differences in topology may have implications for the robustness of such networks to attack and damage, as changes at one layer may have non-obvious implications for the other [12].

**Sociology:** The analysis of social networks has a long history in sociology, and several branches have focused on the interaction between particular modes of interaction and the context in which they occur.

A collection of papers by Adams and Allan explores the various social contexts in which friendship networks are embedded, broadening the traditional focus on isolated dyads to include the web of influences that surround and give structure to a friendship relationship [13]. They identify four levels of context that affect patterns of friendship: personal environment, social network, community and society. They conclude that friendship choices are shaped not only by personal motivations of the individuals involved, but also the contexts, such as economic and domestic circumstances, employment and recreation, in which they are embedded.

Similarly, an intersection between organisational research and social network analysis has recognised that business and employment relationships within an organisation are influenced by social relationships between individuals [14]. One notable difference between organisational and social networks is that the former tend to be structured in a hierarchical fashion, potentially leading to subnetworks that are effectively disconnected below a certain hierarchical level. Social interactions between individuals in different subnetworks can serve to rejoin these components, and it has been observed that 'bridge' individuals, whose social ties join otherwise uncoupled communities, can achieve considerable influence in an organisation. Often, in the design of organisational, business or service structures, the existence of context is ignored or denied–a possible reason why actual system behaviour can differ from planned system behaviour [15].

As previously mentioned, identifying circumstances under which cooperative behaviour could evolve is a problem that has received considerable attention from the modelling community concerns [4–7]. In these models, a distinction is typically made between the processes of interaction, and those constraining or enabling interaction—how individuals choose to behave in interactions with one another (processes on a network) differs fundamentally from the way in which they come to be interacting in the first place (processes that shape the network). During a simulation, individuals typically update both their neighbourhood and their chosen strategy depending on their observations of the behaviour of those around them. Again, at least two modes of interaction can be perceived: the first concerns function and is defined by the rules of the cooperative game in which the individuals are engaged; the second concerns information and reflects the peers on whose behaviour an individual chooses to model their own.

**Social Economics:** The hypothesis that analysis of economic behaviour was incomplete without recognition of the social context in which it was embedded was developed by Granovetter, following on from his work on the importance of weak ties in labour markets [16]. Social context has implications for a wide range of economic behaviours, ranging from market formation and employment to product marketing and occurrence of criminal behaviour. Jackson provides a review of recent developments at the intersection of social economics and economic sociology [17].

A specific example of how social ties can influence economic behaviour can be found in Fafchamps' study of market formation in Sub-Saharan Africa [18]. Because these markets are subject to significantly less central regulation than Western markets, the importance of kin and social relationships as a source of business introductions and a basis for trust is considerably greater. Due to the high costs involved in establishing trading relationships, such links tend to be established slowly and maintained for long periods of time; therefore, the structure of the underlying social network is an important determinant of how markets grow and evolve.

A further role played by networks in markets is in the communication of information: individuals in a market not only trade goods with one another, they also learn details (such as price and quantity) about trades in which they were not directly involved. Such information will influence their future behaviour in the market. Therefore, two separate modes of interaction exist between individuals: actually trading goods, and sharing information about trades [19].

**Politics:** Within the domain of political negotiation, Saam and Sumpter have delineated two separate levels of interaction [20]. The primary level of interaction is between national governments seeking to reach consensus on issues of policy. However, actual negotiation occurs between groups of ministers representing their respective governments. Cross-governmental groupings can develop agendas of their own that may run counter to the interests of their parent governments.

Interactions may also occur between political institutions and broader cultural structures: Ikegami describes the interaction between a hierarchical political structure and horizontal social networks based around aesthetic pursuits such as art and poetry in the Tokugawa period in Japan [21]. She identifies the synergistic intersection of these conflicting social forces and the rapid expansion of communication and trade networks with the origins of Japanese national culture. Critically, she bases her hypothesis on a "multiplex" conception of networks, in which people are connected by economic, social, political and cultural ties.

**Biology:** Multiple modes of interaction are also observed across a range of levels of biological description. In the field of community ecology, local communities are recognised as existing in larger regional biotas that can exert both direct and indirect influence on patterns of variation within a community [22]. In animal societies, individuals can share information about, for example, the viability of prospective mates with one subset of a population, while actual mates are

selected from another, disjoint subset of the population [23]. Within the brain, neurons interact via both chemical and electrical signals, and the network of physical connections between neurons has a different topology to the network of functional interactions [12].

**Technology:** Peer-to-peer computing systems operate by constructing a virtual data communication network on top of routing networks and physical infrastructure, the topology of which may be very different [12]. Furthermore, dynamic processes that occur on data networks can have a strong social component. For example, while infection by computer viruses propagate from computer to computer, knowledge about virus countermeasures tends to spread as a result of more traditional social channels [24]. Finally, online communication has helped reduce the importance of geographical constraints on social network formation, leading to novel patterns of social behaviour [13]. The emergence of online communities, beside being a phenomenon of interest in their own right, has also introduced the problem of how to manage information access: a user may wish to allow other users different levels of access to personal information depending on the nature of their relationship [25].

## 3 Communities: Structure at an Intermediate Scale

A recurring motif appearing throughout the above review is the role played by communities: groups of individuals that are densely linked to each other, but more sparsely linked to other parts of the network. Communities are an intermediate-scale feature of networks: they are larger than the neighbourhood of any one individual, but smaller than the entire network. Research on community structure has focused primarily on the problem of detection; how communities form and their internal and external structure are less clearly understood.

**Community detection:** While community detection algorithms typically focus on identifying structures in empirical data, the types of community structure encountered and the biases inherent in different detection algorithms can provide more general insights into the range of community structures that exist. The most widely used algorithms for detecting communities tend to take an agglomerative or divisive approach: building up (or breaking down) a network to identify groups or communities [8]. A potential problem with these algorithms is that they generate a strictly hierarchical relationship between groups and subgroups, which may not be an accurate reflection of reality.

An alternative approach is to allow overlapping communities. One proposed algorithm uses connected cliques as the basis of defining communities, but allows individual nodes to belong to more than one community [26]. For example, a particular individual may be part of one community based upon their place of employment, and another based upon membership of a sporting club or political party. As a result, a higher level of community organisation (with its own network

topology) becomes visible, in which nodes represent communities and weighted links represent the number of shared individuals between two communities.

**Community formation:** Several models have been proposed that explain how communities can emerge from relatively simple local rules [27, 28]. While these demonstrate how a particular topology can arise as a result of pre-specified mode of social interaction, they do not address the question of how such modes of interaction came into existence: sociality is presupposed. Some models of network formation in economics employ more general (but still strongly constrained) models of interaction based on, for example, game theory; however, these are not reported as producing community structure [4, 5]. One promising approach has used the concept of 'tags' that enable individuals in an unstructured environment to recognise each other and self-organise into communities based on the provision of mutually beneficial skill sets [29, 30]. This allows for the possibility of individual specialisation and the emergence of internal structure within a community.

**Community structure:** The existence of structure both between and within communities is a topic that has only recently attracted attention. There are some cases, such as the relationship between functional modules in protein interaction networks, in which higher order structures between communities have been observed [26, 31]. Conversely, researchers are also beginning to recognise that communities can have an internal, non-homogeneous structure of their own [32, 23]. Such structure is thought to have implications for the ability of animal groups to make collective decisions, either via consensus, or through the actions of leader individuals [33, 34].

The internal structure of a community is also an important component of explaining the emergence of social organisation in primitive human societies. Human social organisation has transitioned through several organisational stages, from small groups, through bands and tribes to more complex chiefdoms [35]. At each transition, the stable integration of multiple lower level groups would have required the existence of suitable organisational structures within the group [36].

## 4 Toward a Conceptual Framework

In this section we carry out a two-stage abstraction of the network domains reviewed above to reveal how their essential features can be captured in a simple, unified framework. Initially, three recurring patterns of network layer interaction can be identified:

**Infrastructure & Traffic:** Perhaps the simplest multivariate network pattern is that involving a physical medium through which some traffic, exchange or flow occurs. The first layer represents the physical infrastructure required to support such traffic; examples of such infrastructure include road, telephone and

neuronal networks. The second layer represents the traffic itself; for example, the vehicles, information and electric impulses that constitute the functional dynamic behaviour of the system.

**Context & Interaction:** The second pattern comprises a context layer, representing network of social, cultural and political ties that define an individual's position in society, and an interaction layer, consisting of a more deliberate set of transactions in which particular individuals have chosen to engage. In comparison to the category above, the context layer represents not a physical infrastructure, but rather an intangible, but very real, web of relationships. This pattern is embodied by the friendship, organisational and economic networks described above.

**Information & Interaction:** The final pattern has as its primary layer a network of functional interactions between individuals; for example, trades, interactions in a cooperative game or the formation of social bonds. The additional layer represents flows between individuals of information that is *about* the primary interaction; for example, the price of goods, payoffs obtained using a particular strategy, or the desirability of mates.

**A Unifying Framework — Milieu & Function:** We suggest that each of these three patterns can be conceived in terms of milieu and function. The milieu is the physical, social or information environment in which a class of functional transactions occur. Functional interactions may be transactions of a physical, economic, social or communicative nature. Rather than conflating these two types of interaction into a single network layer, as is commonly the case, we argue that they should be explicitly separated. Several points are worth noting about this view:

The designation of a network layer as milieu or function may be subjective: what is functional from one perspective may be contextual from another. For example, economic interactions may be viewed as a functional network against the background of a particular social milieu; however, they may in turn contribute to the background milieu against which political interactions take place.

The relationship between milieu and function can be reflexive: For example, an individuals economic circumstances may play a contextual role in influencing the friendship networks they form; however, those social networks may determine the range of economic opportunities in which that individual can participate.

While milieu constrains and enables function, functional transactions may create conditions suitable for the emergence of novel milieus. For example, economic transactions may initially be embedded in a social milieu; however, the existence of a particular network of functional transactions (e.g., a market) may give rise to novel forms of social communication (e.g., financial press).

The milieu of an individual will be dominated by the communities of which it is a member. Understanding how individuals are positioned within communities,

and the relationships that can exist between communities will be a vital part of understanding their effect on individual interactions.

By separating milieu and function, the framework explicitly acknowledges the embedded, ecological nature of social interaction. It incorporates spatiality without being uniquely constrained by the limited dimensionality of physical space. Information about geographical location can be encoded in a network (via constraints on possible neighbours, or weights on edges); however, interactions need not be limited by geographical location. As such, the framework could be used to explore the importance of spatiality on social behaviour, by tuning the degree of influence accorded to geographic location.

The framework does not presume a specific form of functional interaction, such as a Prisoner's Dilemma (or similar) game. One problem with pre-specifying the nature of the functional interaction is that it automatically limits or biases the shape of possible interaction topologies that will emerge. This is similar to the situation in evolution of communication simulations: most early simulations presumed the existence of a communication channel that agents learned or evolved to use, completely negating the question of how communication systems could originate [37]. In the same way a general model of the emergence of social behaviour will require that functional forms of social behaviour be minimally pre-specified.

## 5 Future Directions and Open Questions

**Topological Divergence:** In existing models in which individuals engage in both functional and information sharing interactions, the network topologies utilised for these two processes are typically conflated: individuals share information with the same set of individuals with whom they interact [6]. However, in many real world networks the commonality of these information and interaction networks can not be assumed.

At one end of the spectrum of topological congruence, the milieu and functional networks make be completely coincident. In such cases, what happens to interaction dynamics as these topologies drift apart? At the other end of the spectrum, the milieu may be completely unstructured, in which case, how can structured patterns of interaction emerge at all? More likely, the actual situation will lie somewhere in between these two extremes: a milieu will exist, but will not correspond with the functional topology, in which case, how do properties of the milieu constrain and enable the emergence of functional patterns of behaviour?

**Qualitatively Different Dynamic Processes:** There are several respects in which the interactions that occur at each layer of a multivariate network could be qualitatively different. In several of the domains reviewed above, the dynamics of the process represented by each network layer may occur on significantly different time scales. Generally, individuals will engage in functional transactions more frequently than they make changes to their local neighbourhood, and changes to the local neighbourhood of an individual will tend to occur more frequently than

changes to its milieu. Furthermore, if the interactions at one layer are considered to be the primary dynamic process, the effect of interactions at other layers may act at a meta-dynamic level, modifying the dynamics of the primary process [38]. What implications will this have for the interactions between layers?

**Emergence and Complexification:** In this paper we have focused on describing networks with two layers of interaction. However, once the step has been taken beyond conflating all modes of interaction into a single topology, introducing further distinctions between, for example, the political, economic and cultural circumstances that structure social interactions, would also be possible.

The presence of communities could also be associated with the emergence of new levels of social organisation. The coalescence of individuals into structured groups may enable new types of behaviour and interaction at a community level, such as markets and trade, that did not previously exist. The protection afforded to individuals in a community from defectors may allow internal community structures to develop and support levels of behavioural specialisation that were not previously possible [29, 30]. Ultimately, patterns of interaction within a community could themselves become an object of selection [39, 40]. This then suggests a plausible route for the complexification of social behaviour: Existing milieus support the formation of novel modes of interaction; these new modes of interaction result in the emergence of new types of organisational structure, which in turn serve as the background milieus against which further complexification can occur.

## 6 Conclusions

The milieu of any form of social behaviour is important in that it can constrain and enables the structural and dynamic properties of a network of functional transactions. This idea is not fundamentally new–it has been recognised in many domains: economic, organisational, social, biological and technological. However, we feel that there are many opportunities for contribution by models that explicitly incorporate the contextual milieu in which social behaviour occurs. The milieu of a functional network will often also take the form of a network, although not necessarily one with an identical topology. It is therefore necessary to understand how these two networks interact. The framework described here unifies several related concepts from disparate fields, clarifies the underlying similarity between them and represents a tentative first step toward understanding how the structure of interactions may support the emergence of new forms of social behaviour.

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