Cognitive Re-Use via Emergic Networks

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In this paper we introduce a new cognitive modeling system called Emergic Networks. The Emergic Network system is designed to facilitate functional, nonlinear decomposition with the aim of understanding how different neural systems can interact to produce specific instances of cognitive functionality. The first part of the paper briefly describes the motivation for the system and the second part briefly describes the system and provides a web location for downloading.

Second Order Emergence

The type of emergence we are interested in involves *cognitive re-use* (Anderson, 2010), where the same neural circuits interact in different ways to produce different types of cognitive functionality. That is, the parts, taken together, cannot be considered as a module devoted to a specific cognitive function. There are two ways that emergence can be thought of as underlying cognitive functions. The first is when a cognitive function arises as an emergent property from a dedicated system of neural circuitry. In this case there is a one to one mapping from cognitive function to neural structure. We can call this, *neural to functional emergence*. Attempting to localize brain areas associated with particular cognitive functions would be an example of research based on this assumption (Poldrack, 2010). However, it is also possible for functions directly supported by dedicated neural circuitry to interact and produce *second order functional emergence*; that is, an emergic function arising from the interaction of underlying functions. In the case of second order functional emergence, it would be a mistake to search for a dedicated neural structure designed to produce that function. Instead, the goal would be to explain how such functions emerge through the interaction of underlying functions.

Everyone agrees that some form of neural to functional emergence allows the brain to act in a functional way. However, second order functional emergence is controversial because it implies that the industry of mapping high-level observable functions to specific brain areas is partially or wholly misguided. This issue is represented by two opposing theoretical positions: the *Anatomical Modularity* position and the *Cognitive Re-Use* position. According to the Anatomical Modularity position, each cognitive function is implemented by a dedicated neural system (Bergeron, 2007). In contrast, the Cognitive Re-Use position (Anderson, 2010) asserts that most or all cognitive functions are the product of underlying, interacting functions that can play different roles in the formation of different cognitive functions. Theories related to the idea of Cognitive Re-Use include: *neural exploitation*, *shared circuits model*, *neuronal recycling*, *massive redeployment*, *highly connected hubs*, *descent-with-modification modularity*, the *Lego model*, *fine-grained information processing operations* and *distributed processing* as mentioned by Anderson.

In terms of emergence, the anatomical modularity position seems to be associated with an implicit assumption that the modules will interact in an additive, linear manner to produce easily decomposable aggregate behaviours. In contrast, the cognitive re-use position seems like it would almost require some form of non-linear interaction or emergence to get it to work. This difference is possibly due to the fact that the assumed output of anatomical modules is often symbolic in nature, whereas the functions in cognitive re-use would be primarily pre-symbolic; that is, functions that need to be combined to produce the ability to process symbols (or to act as if we can process symbols).

Some cognitive modeling systems include recurrent interactions that can lead to emergence. For example, recurrent networks employ recurrent feedback loops, CLARION (Helie & Sun, 2011) has explicit modules for top down and bottom up processes that can potentially produce recurrent feedback, and ACT-R has been used to model recurrent feedback between agents (e.g., West, Stewart, Lebiere, & Chandrasekharan, 2005). Recurrent feedback also plays an important role in Dynamic systems models of cognition (Krech, 1950) and in various neural models, such as NENGO (Eliasmith & Anderson, 2003). However, while all of these systems can employ feedback to achieve interesting emergent effects, none of these systems were designed specifically to model and study the role of second order emergence in cognition. Dynamic systems theory is designed for studying emergence, but it is not a modeling system. It is a collection of mathematical tools for analyzing dynamic systems. A dynamic systems model must be constructed mathematically and there are no cognitive or neural constraints on how this should be done. Spiking neural models are designed to model neural to cognitive emergence. Such systems can be used to model second order functional emergence but the process would be guided and constrained by bottom up, neural constraints. This is a good thing, but a more complete research program would also involve exploring this from a purely functional point of view, as we are not yet completely sure what the neural constraints should be.

The emergic network is designed to explore how lower level functions are combined and re-used to produce multiple instances of higher level functionality. Emergic networks are non-symbolic and in some ways similar to spiking neuron models. In particular, the emergic units that make up the networks are similar to clusters of neurons that perform a specific function and the connections between the emergic units are functionally similar to the neural connections between clusters. Also, similar to neural systems, emergic networks process information in a continuous manner. However, the point of emergic networks is to understand emergence based on functionality, not neural behaviour. As far as we know, the emergic network is the first cognitive modeling system specifically designed to model second order functional emergence and re-use.

Emergic Networks

The decomposition of intelligent behaviour into cognitive functions and structures has traditionally progressed by hypothesizing macro-level functions that emerge from a minimal interaction between localized brain modules. An alternative approach considers finer grained brain modules as realizing micro-level functions that are extensively reused (M. L. Anderson, 2010) and interact to cause higher order functions to emerge, often in a non-linear fashion. However, this latter approach greatly complicates the scientific reduction of cognition not only because of an extra level of non-linear decomposition, but mostly due to a lack of characterization and experience in such an analytical space. Emergic networks are meant as a step forward in clarifying and dealing with this issue.

An *emergic network* consists of a connected set of *emergic units*, each forming a micro-level portion of functional computation and behaviour. An emergic unit computes a function that can be represented mathematically or by computer code. Emergic units have input and output *ports* that connect them to other emergic units through *links*. Links transport *values* between the units. The values can take any mathematical form (e.g., numbers, vectors, and statistics). Links are unidirectional and have a scaling factor that is set to 1 by default. Input and output ports can be connected to multiple links. By default, link values are summed at input ports while an output port will duplicate its value to all destinations.

The emergic network architecture is synchronous, with links having a minimal delay of one tick. That is, the delivery of values through the links is clocked so that all values arrive at the same time. The values flowing around the network are intended to represent small changes, i.e., to approximate a physical system of continuous change and interaction (Rumelhart, McClelland, & Group, 1987). Emergic networks model asynchronous behaviour by setting time delays (counted in ticks) small enough for computing the effective functions of emergic units in an incremental fashion.

It is interesting to note that although the emergic network was developed independently, the structure we have just described is very similar to NENGO, which is a spiking neuron modeling system. This is can be attributed to the fact that both systems are concerned with identifying the basic units of neural computation. In NENGO the functions carried out by the emergic units are carried out by realistic spiking neuron models. However, the focus of these systems is different. The focus of NENGO is to consider realistic neural constraints when modeling systems of neural computation. The focus of emergic networks is to model second order emergence and cognitive re-use. That is, to explore how different functions can interact to produce cognitive phenomena. The goal with emergic networks is to work out cognitive design principles that might otherwise be overlooked by assuming a one to one mapping between cognitive functions and neural units.

The code for building Emergic Networks can be downloaded from http://emergic.upwize.com/?page_id=6. Currently we are working on an emergic network model to produce a unified account of low level visual effects such as filling-in. Preliminary results are available at http://emergic.upwize.com/?page_id=31.

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