Fractally-organized Connectionist Networks:
Conjectures and Preliminary Results

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Abstract A strict interpretation of connectionism mandates complex networks of simple components. The question here is, is this simplicity to be interpreted in absolute terms? I conjecture that absolute simplicity might not be an essential attribute of connectionism, and that it may be effectively exchanged with a requirement for relative simplicity, namely simplicity with respect to the current organizational level. In this paper I provide some elements to the analysis of the above question. In particular I conjecture that fractally organized connectionist networks may provide a convenient means to achieve what Leibniz calls an "art of complication", namely an effective way to encapsulate complexity and practically extend the applicability of connectionism to domains such as sociotechnical system modeling and design. Preliminary evidence to my claim is brought by considering the design of the software architecture designed for the telemonitoring service of Flemish project “Little Sister”.

1 Introduction

Connectionism—also known as parallel distributed processing (PDP) and artificial neural networks (ANN)—has been successfully applied to several problems, including pattern and object recognition, speaker identification, face processing, image restoration, medical diagnosis, and others [1], as well as to several cognitive functions [2]. In connectionism,

“Processing is characterized by patterns of activation across simple processing units connected together into complex networks. Knowledge is stored in the strength of the connections between units.” [2]

The accent on simplicity is also present in another definition of connectionism:

“The emergent processes of interconnected networks of simple units” [3].

Similarly, in [4] Rumelhart, Hinton, and McClelland introduce PDP as a model based on a set of small, feature-like processing units.

I believe it is important to reflect on the simplicity requirement expressed in the above definitions. Regardless of their position and role, the nodes of a connectionist network are intended as simple parts. This is the case also when
the network is organized into a complex hierarchy of layers. Simplicity pertains to the function of the role but also to the role played by the node, which is tuneable though statically defined.

My question here is: is this simplicity to be interpreted in absolute terms? If that would be the case, then individual nodes may not represent complex behaviors resulting from the collective action of aggregations of other nodes. In this sense, absolute simplicity of the nodes may limit the applicability of connectionism. How could one easily and comfortably model, e.g., a complex social organization, or a digital ecosystem, or a biological organism, only by reasoning in terms of simple nodes? Such an endeavour would be the equivalent to writing a complex software application with no mechanism to encapsulate complexity (such as software modules, services, aspects, and components).

The rest of this article is to detail the reasons why my answer to the above question is “no”. In fact, my conjecture is that absolute simplicity might not be an essential attribute of connectionism, and that it may be effectively exchanged with a requirement for relative simplicity, namely simplicity with respect to the current organizational level.

A second conjecture here is that a convenient hybrid form of connectionism would be that of fractally organized connectionist networks (FOCN). More formally, fractal connectionism would replace the absolute simplicity requirement of “pure” connectionism with the following two properties:

**Fractal Organization:** FOCN nodes are fractally organized [5]. This in particular means that nodes have a dynamic organizational role that depends on the context and on system-wide organizational rules—the so-called “canon”. In other words, regardless of their level in a fractal hierarchy, the nodes obey the same canon and switch between, e.g., management and subordinate, or input and output roles, depending on the situation at hand. The nodes become thus organizationally homogeneous. In fractal organizations nodes are typically called holons [5] or fractals.

**Increasing Inclusiveness:** FOCN nodes function as modules that are at the same time monadic (namely, atomic and indivisible) with respect to the layer they reside in and composite organizations of parts residing in lower layers [6]. Through these “organizational digits” absolute simplicity becomes relative simplicity. As nonterminal symbols in context-free grammars, every node in FOCN is in itself both a network and the “root” of that network.

In what follows I provide some elements towards a discussion of the benefits of coupling fractal organization with connectionism.

– In Sect. 2 I first identify in the so-called Art of Complication of Leibniz the ancestor of “relative simplicity” and fractal organization.
– In Sect. 3 I briefly recall the major aspects of fractal social organizations, an organizational model for sociotechnical systems and cyber-physical societies. In particular in that section I compare the major differences between PDP and fractal social organizations. As a result of that comparison, fractal social organizations are interpreted as a FOCN organizational model.
A practical application of said model is the subject of Sect. 4: the web service architecture and middleware developed in the framework of Flemish project “Little Sister”.

Conclusions and next steps are then drawn in Sect. 5.

2 Leibniz’ Art of Complication

When the tables of categories of our art of complication have been formed, something greater will emerge. For let the first terms, of the combination of which all others consist, be designated by signs; these signs will be a kind of alphabet. It will be convenient for the signs to be as natural as possible—e.g., for one, a point; for numbers, points; for the relations of one entity with another, lines; for the variation of angles and of extremities in lines, kinds of relations. If these are correctly and ingeniously established, this universal writing will be as easy as it is common, and will be capable of being read without any dictionary; at the same time, a fundamental knowledge of all things will be obtained. The whole of such a writing will be made of geometrical figures, as it were, and of a kind of pictures—just as the ancient Egyptians did, and the Chinese do today. Their pictures, however, are not reduced to a fixed alphabet [. . . ] with the result that a tremendous strain on the memory is necessary, which is the contrary of what we propose. [7]

As brilliantly discussed in [6], hierarchies are a well-known and consolidated concept that pervades the organization of both our societies and biological systems. Particularly interesting and relevant to the present discussion are so-called nested compositional hierarchies, defined in the cited reference as “a pattern of relationship among entities based on the principle of increasing inclusiveness, so that entities at one level are composed of parts at lower levels and are themselves nested within more extensive entities”. As mentioned in Sect. 1, increasing inclusiveness ($I^2$) practically realizes modularity and relative simplicity by creating matryoshka-like concepts that are at the same time monadic and composite. The same principle and the same duality may be found in the philosophy of Leibniz [8,9]. The Great One introduces the concept of substances, namely

“networks of other substances, together with their relationships. [. . . A substance is a] concept-network packaging a quantum of knowledge that becomes a new digit: a new concept so unitary and indivisible as to admit a new pictorial representation—a new and unique [pictogram]” [8].

Leibnizian pictograms were thus an application of the $I^2$ principle to knowledge representation. Pictograms of substances are thus at the same time knowledge units and knowledge networks; unique digits and assemblies of lower level
signs and pictograms; which are obtained through some well-formed method of composition—some compositional grammar. Leibniz called the corresponding language “Characteristica Universalis” (CU): a knowledge representation language in which any conceptual model would have been expressed and reasoned upon in a mechanical way. The “engine”, or algebra, for crunching CU expressions was called by Leibniz Calculus Ratiocinator. A parser reducing a sentence in a context-free language into a nonterminal symbol is a natural example of a Calculus Ratiocinator. As mentioned in [8],

“Such pictograms represent modules, namely knowledge components packaging other ancillary knowledge components. In other words, pictograms are Leibniz’s equivalent of Lovelace’s and Turing’s tables of instructions; of subroutines in programming languages; of boxes in a flowchart; of components in component-based software engineering.”

Interestingly enough, the same principle and ideas were recently re-introduced in Actor-Network Theory [10,11] through the concepts of punctualization and blackboxing.

3 Connectionism vs. Fractal Social Organizations

Fractal social organizations (FSO) are a class of socio-technical systems introduced in [12,13]. FSO may be concisely described as a fractal organization of nodes called service-oriented communities (SoC’s) [14]. Such nodes are “organizationally homogeneous”, meaning that they provide the same, relatively simple organizational functions regardless of their place in the FSO network. Each node is a fractal—in the sense specified in Sect. 1—and may include other nodes, thus creating a matryoshka-like structure. A special node within each SoC punctualizes the whole SoC. Such node is called representative and is at the same time both a node of the current SoC and a node of the “higher-ups”—namely the SoC’s that include the current SoC. Nodes publish information and they offer and require services. Information and service descriptions reach the representative and are stored in a local registry. The arrival of new information and service descriptions triggers the execution of response activities, namely guarded actions that are enabled by the availability of data and roles. Missing roles triggers so-called exceptions: the request is forwarded to the higher-ups and the missing roles are sought there. Chains of exceptions propagate the request throughout the FSO and result in the definition of new temporary SoC’s whose aim is executing the response activities. The lifespan of the temporary SoC’s is limited to the execution of the activities they are associated with. Due to the exception mechanism, the new temporary SoC’s may include nodes that belong to several and possibly “distant” SoC’s. As such they represent an overlay network that is cast upon the FSO. Because of this I call them “social overlay networks” (SON).

In order to assess the relationship between FSO and PDP, now I briefly review the components of the PDP model as introduced by Rumelhart, Hinton,
and McClelland in [4]. For each component I highlight similarities and “differentiae” [15], namely specific differences with respect to elements of the FSO model [16].

In what follows, uncited quotes are to be assumed from [4].

Figure 1. Space of all possible states of activation of an FSO with nine agents and six roles. Roles are represented as integers 0, . . . 6. Role 0 is played by four agents, all the other roles can be played by one agent only.

“A set of processing units”. In PDP these units may represent “features, letters, words, or concepts”, or they may be “abstract elements over which meaningful patterns can be defined”. Conversely, in FSO those units are actors, identified by a set of integers [12]. A major difference is that in
FSO actors can be “small, feature-like entities” but also complex collections thereof. Another difference of FSO is given by the presence of a special role—the above mentioned representative.

− “A state of activation”. In PDP this refers to the range of states the processing nodes may assume over time. In PDP this range may be discrete or continuous. A simple example is given by range \{0, 1\}, interpreted as “node is inactive” and “node is active”.

In FSO the state of activation is simply whether an actor is involved in an activity and thus is playing a role, or if it is inactive. In [12] I described the global state of activation of FSO by means of two dynamic systems, \( L(t) \) and \( R(t) \), respectively representing all inactive and all active FSO actors at time \( t \). Pictures such as in Fig. 1 represent the space of all possible states of activation of an FSO. Actors can request services or provide services—which corresponds to the input and output units in [4]. The visibility of actors is restricted by the FSO concept of community: a set of actors in physical or logical proximity, for the sake of simplicity interpreted as a locus (for instance a room; or a building; or a city, etc.) Non-visible actors correspond to the hidden units of PDP [4].

− The behaviors produced by the activated actors of an FSO correspond to what Rumelhart et al. call as the “output of the units” in PDP. In FSO, this behavior is cooperative and is mediated by the representative node. In the current implementation of our FSO models, a node’s output is equal to the state of activation. In other words, in FSO an actor is currently either totally involved in playing a role or not at all. Future, more realistic implementations will introduce a percentage of involvement, corresponding to PDP’s unit output. This will make it possible to model involvement of the same actor in multiple activities.

− Nodes of a PDP network are also characterized by a “pattern of connectivity”, namely the interdependencies among the nodes. Each PDP node, say node \( n \), has a fan-in and a fan-out, respectively meaning the number of nodes that may have an influence on \( n \) or the number of nodes that may be influenced by \( n \). Influence has a sign, meaning that the corresponding action may be either excitatory or inhibitory. Conversely, in FSO I distinguish two phases—construction and reaction. In construction, the only pattern of connectivity is between the nodes of an SoC and the SoC representative. This pattern extends beyond the originating SoC by means of the mechanism of exception and results in the definition of a new temporary SoC—the already mentioned SON. Once this is done, reaction takes place with the enaction of all the SON agents. Different patterns of activity may emerge at this point, representing how each SON agent contributes to the emerging collective behavior of the SON.

− Another element of the PDP model is the “rule of propagation”, stating how “patterns of activities [propagate] through the network of connectivities” in response to an input condition. In FSO, propagation is simply regulated by the canon, namely the rules of the representative and of the exception [16].
– So-called “activation rule” is a function modeling the next state of activation given the current one and the state of the network. In the current model, FSO activation rules are very simple and dictate that any request for enrollment to an inactive role is answered positively. A more realistic implementation should model the propensity and condition of a node to accept a request for enrollment in an activity. Factors such as the availability of the node, its current output level (namely, degree of involvement), and even economic considerations such as intervention policies and “fares” should be integrated into our current FSO model.

– Another important component of the PDP model is “Modifying patterns of connectivity as a function of experience”. As suggested in our main reference, “this can involve three types of modifications:
  • The development of new connections.
  • The loss of existing connections.
  • The modification of the strengths of connections that already exist.”

As mentioned above, in FSO we have two types of connections:
1. “Institutional” connections, represented by relationships between organizationally stable SoC’s. An example is a “room” SoC that is stably a part of a “smart house” SoC, in turn a stable member of a “smart building” SoC.
2. “Transitional” connections, namely connections between existing SoC’s and new SON’s.

As I suggested in [12], experience may play an important role in FSO too. By tracking the “performance” of individual nodes (as described, e.g., in [17,18]) and individual SON’s the structure and processing of an FSO may evolve. In particular, transient SON may be recognized as providing a recurring “useful” function, and could be “permanentified” (namely, turned into a new permanent SoC). An example of this may be that of a so-called “shadow responder” [19] providing consistently valuable support in the course of a crisis management action. Permanentification would mean that the shadow responder—for instance, a team of citizens assembled spontaneously and providing help and assistance to the victims of a natural disaster—would be officially or de facto recognized and integrated in the “institutional” response organizations, as suggested in [20,21].

Similarly, SoC that repeatedly fail to provide an effective answer to experienced situations may cease to make sense and be removed from the system. Reorganizations are a typical example of cases in which this phenomenon may occur.

The PDP concept of the strength of connection is also both interesting and relevant to the present discussion. A connection between two nodes may be realized as being “mutually satisfactory” (what is sometimes called as a “win-win”) and in the long run may strengthen by producing a stable connection. Mutualistic relationships such as symbiosis and commensalism are typical examples of this phenomenon. Their role in FSO has been highlighted in [22].

– A final element in PDP is the “representation of the environment”. This is a key component in the FSO model too, though with a very different
interpretation of what an environment is. In PDP environment is “a time-varying stochastic function over the space of input patterns”, while in FSO is is the set of probabilistic distributions representing the occurrence of the input events. As an example, environment is interpreted as FSO also as the rate at which new requests for assistance enter the FSO.

4 The Little Sister Software Architecture

Little Sister (LS) is the name of a Flemish ICON project financed by the iMinds research institute and the Flemish Government Agency for Innovation by Science and Technology. The project run in 2013 and 2014 and aimed to deliver a low-cost telemonitoring [23] solution for home care. Two are the reasons for mentioning LS here:

1. LS may be considered as a connectionist approach to telemonitoring: in fact in LS the collective action of an interconnected network of simple units [24] (battery-powered mouse sensors) replaces the adoption of more powerful and expensive complex devices (smart cameras; see Fig. 2).

2. The LS software architecture realizes a simplified FSO: a predefined set of SoC’s realizes the structure exemplified in Fig. 3.

The cornerstone of the LS software architecture is given by web services standards. As discussed in [13],

"the LS mouse sensors are individually wrapped and exposed as manageable web services. These services are then structured within a hierarchical federation reflecting the architectural structure of the building in which they are deployed [25]. More specifically, the system maintains dedicated, manageable service groups for each room in the building, each of which contains references to the web service endpoint of the underlying sensors (as depicted in layers 0 and 1 in Fig. 3). These ‘room groups’ are then aggregated into service groups representative of individual housing
Figure 3. Exemplification of the LS Fractal Social Organization.

units. Finally, at the highest level of the federation, all units pertaining to a specific building are again exposed as a single resource (layer 3). All services and devices situated at layers 0–3 are deployed and placed within the building and its housing units; all services are exposed as manageable web services and allow for remote reconfiguration.”

Absolute simplicity is here traded with modularity and relative simplicity: each “level” hosts nodes that are “simple” with respect to the granularity of the action. Correspondingly, each layer hosts services of increasing complexity, ranging from image to motion processing and from raw context perception to situation identification [26]. Each SoC is managed by a representative implemented as a module of a middleware. Said middleware is based on a fork of Apache MUSE—“a Java-based implementation of the WS-ResourceFramework (WSRF), WS-BaseNotification (WSN), and WS-DistributedManagement (WSDM) specifications” [27] on top of Axis2 [28], and partially implements the WSDM-MOWS specification [29] (Web Services Distributed Management: Management of Web Services).

It is the LS middleware component in each SoC that manages the FSO canon: events produced by the local nodes are received by the middleware by means of a standardized, asynchronous publish-and-subscribe mechanism [30]. The middleware then verifies whether any of the local nodes may respond with some actuation logic. If so, the local node is appointed to the management of the response; otherwise, an exception takes place (see Sect. 3) and the event is propagated to the higher-up SoC. Given the fact that, in LS, a predefined population of nodes and services is available and known beforehand, the selection and exception mechanisms are simple and have been implemented by annotating events and services with topic identifiers. In a more general implementation of the
FSO model, selection and exception require semantic description and matching support as discussed in [31].

5 Conclusions

At a low level of ambition but with a high degree of confidence [General Systems Theory] aims to point out similarities in the theoretical constructions of different disciplines, where these exist, and to develop theoretical models having applicability to at least two different fields of study. At a higher level of ambition, but with perhaps a lower degree of confidence it hopes to develop something like a “spectrum” of theories—a system of systems which may perform the function of a “gestalt” in theoretical construction. Such “gestalts” in special fields have been of great value in directing research towards the gaps which they reveal. [...] Similarly a “system of systems” might be of value in directing the attention of theorists toward gaps in theoretical models, and might even be of value in pointing towards methods of filling them.

General Systems Theory—The Skeleton of Science
K. Boulding

In this work I considered two seemingly unrelated “gestalts”: connectionism and fractal organization. By reasoning about them in general and abstract terms, I observed how connectionism could possibly benefit from the application of I², namely the principle of increasing inclusiveness, and interpret processing nodes’ simplicity in relative rather than absolute terms. I have conjectured that, in so doing, connectionism would further extend its applicability and expressiveness. I called fractally-organized connectionist networks the resulting hybrid formulation. I then introduced a model of fractal organization called FSO and I compared the key elements of parallel distributed processing with corresponding assumptions and strategies in FSO. As a practical example of the hybrid model I discussed the software architecture of Flemish project “Little Sister”—a web services-based implementation of a “fractally connectionist” system. As observed by Boulding [32], the above discussion put to the foreground a number of oversimplifications in the current FSO model. As a consequence, our future research shall be directed towards the gaps that the above discussion helped revealing, in particular extending the FSO model with more complete and general elements of the connectionist models.

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