WLIMES, the Wandering LIMES: Towards a Theoretical Framework for Wandering Logic Intelligence Memory Evolutive Systems

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Abstract. This paper compares two complementary theories, Simeonov's Wandering Logic Intelligence and Ehresmann's & Vanbremeersch's Memory Evolutive Systems, in view of developing a common framework for the study of multi-scale complex systems such as living systems. It begins by a brief summary of WLI and MES, then analyzes their resemblances and differences. Finally, the article provides an outlook for a future research.

Keywords: Wandering logic intelligence, Memory evolutive systems, Hierarchy, Emergence, Self-organization, Autopoiesis, Genetic transcoding, Virtualization, Distribution, Non-locality, Category theory.

1 Introduction

This paper is divided in 3 parts:

(i) The first one gives a brief summary on the Wandering Logic Intelligence (WLI); a biology-inspired theoretical and practical framework for designing evolutionary communication architectures and their services and applications in terms of an always growing model of ever changing software and hardware. The WLI approach represents a next step of network virtualization and evolution of application- and user-aware networks as adaptive systems consolidating both network element and infrastructure flexibility. Now this approach is taken back to biology to model the operational semantics of complex emergent formations and processes.

(ii) The second part presents the main ideas at the basis of the Memory Evolutive Systems; a dynamic model for self-organized multi-scale complex systems such as living, cognitive or social systems; these systems have a hierarchy of components changing over time, and their dynamic is modulated by the cooperation/competition between a net of agents, the co-regulators, each operating locally with its own rhythm, function and logic. The model is based on a dynamic category theory which gives tools for representing the notion of hierarchy. It emphasizes 2 main properties of such systems: the Multiplicity

Principle, a kind of 'flexible redundancy' which is shown to be at the root of the emergence of higher complexity, robustness and flexibility; and the synchronicity laws that the co-regulators must respect and which generate cascades of failures/repairs at different levels.

(iii) The third part compares the above two theories and stresses their complementarity. It suggests how they could be merged into a common framework, the Wandering LIMES, which would add more structure on the WLI, and more quantifications to make the MES accessible to some sort of "computation".

2 The Wandering Logic Intelligence

The following paragraphs provide a summary of the WLI theory.

2.1 Overview

The *Wandering Network, WN* (Simeonov, 1998, 1999a, 2001) is a generalization for programmable and active networks based on a fomalism called the *Wandering Logic Intelligence*, *WLI* (Simeonov, 1999b, 2002a/b) and defined by:

- flexible, multi-modal specialization of network nodes as virtual subnetworks;
- mobility and virtualization of the net functions in hardware und software;
- self-organization as multi-feedback-based topology-on-demand.

The Wandering Network exhibits three essential characteristics:

1. it is a *hyper*active network which means that it is programmable and reconfigurable, incl. the network hardware up to the gate level;
2. it is a runtime extensible and exchangeable network in terms of both software and hardware components (a *wandering network)*;
3. it is an evolutionary network which realizes *adaptive* self-distribution and replication of sub-networks:
    - by guided or autonomous node and component mobility in terms of hardware;
    - by including network engineering information in the mobile code of the active packets and applying *genetic transcoding* mechanisms in the active mobile nodes.

In particular, network elements can contain several exchangeable modules capable of executing diverse network functions in parallel. These functions can be invoked, transported to or generated in the nodes upon delivery of mobile code containing programs about the node’s behaviour. An essential characteristic of the WLI approach is, however, the inherent ability to instantly spread out information about architectural changes among the nodes by encoding *executable re-constructon (genetic) instructions* within the transported active packets – as *“network” genes, N-genes.*

The *Wandering Logic Intelligence* (Simeonov, 1999b, 2002a/b) is a theory for modelling Wandering Networks. WLI generalizes active networks' capsules (Tennenhouse, et al., 1996; Kulkarni & Mindem, 1999) in *shuttles* as relatively autonomous mobile components including both programs and data possibly encoded in a language with (semantic) references to ships (active mobile network nodes, also called *netbots*) and other shuttles within the same or a different flow (protocol). Furthermore, the WLI model allows the creation of new capsules/shuttles (or the replication of "old" ones) in the intermediate netbots. In addition, a special class of shuttles, called jets are allowed to replicate themselves and to create, remove, or modify other capsules and resources in the network.

The essential contributions of the WLI model and the resulting Wandering Network are:

1. Role Change: The *role* of the network node within a particular virtual architecture can change during its operation. The new functionality is either resident on the node and waiting to be activated, i.e. it is not yet involved in the next step virtual scheme, or transferred to the destination node.
2. Parallel Roles: The execution of the parts of a distributed algorithm can be performed within the different roles of an active node's / ship's, configuration.
3. *Node Genesis ("N"-geneering):* encoding and embedding the structural information about a mobile node, the ship, and its environment into the executable part of the active packets, the shuttles (Simeonov, 2002c).
4. *Non-local Interdependence:* undeterministic distribution of system/network properties by means of active packets (shuttles) containing both code/commands and data.

Now, we propose to use WLI for modeling biological networks. In the following section we present the WLI design principles.

2.2 The WLI Principles

The goal of the *Viator* approach (Simeonov, 2002b) is to propose and demonstrate a simple and flexible mechanism for network evolution based on the emergence, change and movement of functional units within a given physical network infrastructure which recognizes its own boundaries. Such a network is known as *autopoietic system.*

The Wandering Network is based on the following WLI principles:

1. Dualistic Congruence (DC)
2. Self-Reference (SR)
3. Multidimensional Feedback (MF)
4. Pulsating Metamorphosis (PM)
5. Resource Usage and Availability (RUA)

The first four principles were defined in (Simeonov, 2002a/b), whereas the last one was added later in the HiPeer architecture (Wepiwé, & Simeonov, 2005-2006) which was based on the WARAAN algorithm (Simeonov, 2002a/c). The WLI program implementation is based on Lamport's Temporal Logic of Actions, TLA (Lamport, 1994) for generating C/C++ code.

2.2.1 The Dualistic Congruence Principle

The Wandering Logic model is based on: a) the dual nature of the *ployons*, the active (mobile) network component abstractions in their two manifestations, *ships/netbots* and *shuttles*, and b) on their congruence. The Dualistic Congrunce Principle (DCP) states that a ship's architecture reflects the shuttle's structure at some previous step and vice versa.

Thus, *ships* are both reconfigurable computing machines and active mobile nodes in terms of hardware and software. Shuttles transport software which can activate / replace ships and their components/aggregates.

A ship processing shuttles can change its state and re-configure its resources and connections *a posteriori* for further actions. In addition, it can adapt (itself) *a priori* to communications in such a way that it can anticipate and *best-match the structure of the shuttles at their arrival time.* Finally, a ship can also change the state of a shuttle.

*Shuttles***,** in turn, can be e.g. interpreted by a reconfigurable computing element inside a ship to build and/or invoke new functions. A shuttle approaching a ship can *re-configure itself* becoming a *morphing* packet to provide the desired interface and match a ship's requirements. This operation can be e.g. based on the destination address and on the class of the ship included in this address.

2.2.2 The Self-Reference Principle

Definition 1. The following characteristics identify a wandering network as *self-referring*:

- Each mobile node / ship knows best its own architecture and function, as well as *how* and *when* to display it to the external world. Ships are required to be *fair* and *cooperative* w. r .t. the information they display to the external world; otherwise they are excluded from the network community.
- Ships, are living entities: they can be born, live and die. Ships can also organize themselves into clusters based on one or more *feedback* mechanisms. Communication between the ships is realized through exchanging programs and data by means of *shuttles,* active packets, which may also contain encoded structural information about the ships or parts of the network itself. The structural information can be used to maintain the operation of the network as a whole, as well as to invoke desired or necessary changes in the infrastructure through service utilization and components' feedback.
- Each ship can acquire or *learn* some other function and extend its architecture by some additional functional components in software or hardware, as well as to become a (temporary) aggregation (a cluster) of other nodes with a joint architecture and functionality.

The *Self-Reference Principle (SRP)* addresses the *autopoiesis* and autonomy properties of the WN elements.

2.2.3 The Multidimensional Feedback Principle

The *feedback principle* in network engineering is well known in protocol design for applications such as traffic control. However, not all degrees of freedom have been exploited until now. A network offers much better opportunities to address e.g. traffic issues on a *per-service* basis than on per-devices alone. This actually corresponds to a dynamic change (re-configuration) of the network topology and resources in *multiple dimensions*. A Wandering Network provides a number of means for such a solution. Here is where the multiple dimensions come from. The number of such interoperating feedback dimentions is virtually unlimited.

2.2.4 The Pulsating Metamorphosis Principle

The generic process of network self-creation and self-organization is referred to as the *Pulsating Metamorphosis Principle (PMP).*

Definition 2. The *Pulsating Metamorphosis Principle* postulates that:

- There are two types of moving network functionality from the center to the periphery and vice versa inside a Wandering Network which are referred to as *pulsating metamorphosis*: horizontal, or inter-node, and vertical, or intra-node, transition.
- A net function can be based on one or more facts (events, experiences). The combination of net function and facts is called a *knowledge quantum* (*kq)* in the WLI model. Knowledge quanta are a new type of capsules which are distributed via shuttles in the Wandering Network. Net functions and facts can be recorded by, stored in and transmitted between the ships. They can be selectively processed inside the ships and distributed throughout the Wandering Network (WN) in an arbitrary manner.
- Facts have a certain *lifetime* in the Wandering Network. This lifetime depends from the clustering of facts inside the ships (knowledge base), as well as from their transmission intensity, or bandwidth (known as "weight"). As soon as a fact does not reach its frequency threshold, it is deleted to leave space for new facts. Since net functions are based on facts, their lifetime (and hence, the lifetime of the corresponding network constellations) depends on the facts. Which facts determine the presence of a particular function inside the Wandering Network is defined individually for each function. Through the exchange and generation of new facts, it is possible to modify functions in order to prolong their lifetime. The *kq* lifetime is defined by the lifetime of its network function. A modification of a net function is determined by a new set of knowledge quanta.
- Network elements can encode and decode their state in knowledge quanta. This mechanism is called *genetic transcoding.*
- A net function can emerge on its own (the *autopoiesis* principle) by getting in touch with other net functions (i.e. states and net constellations), facts, user interactions or other transmitted information. *The function defines the network and vice versa.* We call this new property *network resonance.*

The network resonance is the leading WLI characteristic and can be regarded as a kind of adaptive meta-policy for network development. With its help, clusters and constellations of network elements or their functions can be (self-)correlated, i.e. structurally coupled, and/or (self-)organized in groups, classes and patterns and stored in the cache of the single nodes/ships or in the (centralized) long term memory of the network, in order to be used later as a decision base or as a development program for particular processes in the network.

The above four principles define the overall concept framework of the Wandering Network, (Simeonov, 1998-2001).

2.2.5 The Resource Usage and Availability Principle (RUAP)

The Resource Usage and Availability Principle (RUAP) was defined and realized in the HiPeer architecture (Wepiwé, & Simeonov, 2005-2006). It simply states that the more the network resources are used, the more stable and reliable, i.e. the more strain-hardened the architecture becomes. This principle acts against the high plasticity of the other four principles and stimulates the development of reinforced structures and pathways. The latter capability is closely related to the AI concepts of pattern recognition, learning and self-awareness, thus representing an important advantage in evolutionary and cognitive networking which can be further developed towards truly intelligent, i.e. *conscious* network environments and infrastructures. RUA can have many different realizations in terms of naturalistic computation; HiPeer is only one of them.

3 The Memory Evolutive Systems Theory

The Memory Evolutive Systems (MES) give an integrative dynamic model for self-organized multi-scale evolutionary systems, such as biological, neuro-cognitive or social systems. Such systems are characterized by several kinds of multiplicities:

i. a tangled hierarchy of interconnected complexity levels varying over time;
ii. existence of multiform components (*Multiplicity Principle*) at the root of emergence and flexibility;
iii. a multi-agent multi-temporality self-organization, in which each agent (called *co-regulator*) has its own logic and operates stepwise at its own rhythm, though the discrete time-scales of the agents must synchronize in function of the global continuous 'time-clock' (*Synchronicity Laws*);
iv. a hierarchical central 'memory', both robust and flexible that allows for learning, self-repair and adaptation.

This model, developed by A. Ehresmann and J.-P. Vanbremeersch since 1987 (cf. the book of Ehresmann & Vanbremeersch 2007 for more details) is based on a 'dynamic' category theory integrating Time.

To account for the dynamic 'in progress', the system is not represented by a unique category (as in models giving a logic model of the invariant structure; e.g., Rosen, 1985 and his followers: Louie, 2009, Nomura 2012), but by an *Evolutive System* **K**, that is a family of 'configuration' categories K_t indexed by Time, and partial 'transition' functors between them.

3.1 Description of a MES. Multiplicity Principle and Its Consequences

3.1.1 MES as an Evolutive System K

The category K_t represents the configuration of the system at time *t*; its objects model the states of the components of the system existing at *t*, the morphisms (called *links*) channels through which information (or constraints...) can be transmitted between them. Each link has a *propagation delay* and can be *active* or *passive* depending if some information is transmitted or not through it around *t*. In the WLIMES project, this transmission will be effected by a *shuttle* in the WLI sense.

The transition from K_t to $K_{t'}$ connects the state of a component C or a link at *t* to its new state at *t'*, if it still exists at *t'*. This transition allows measuring the changes between 2 'snapshots' of the system but does not describe the continuous dynamic which has generated them.

3.1.2 The Hierarchy of Components

The components around a time *t* are divided into complexity levels, so that a component C of level n+1 acts as the aggregate of a pattern P of linked lower level components which it 'binds'. Thus C has the same functional role that its decomposition P acting collectively. Formally C is modeled by the categorical "*colimit*" of P (or inductive limit, Kan, 1958).

While a pattern has at most one colimit (up to isomorphisms), different patterns may have the same colimit. It allows explaining how a complex component C may preserve its *complex identity* (or "class identity" in the terms of Matsuno (2012)) while its composition varies; for instance the molecules of a cell are progressively replaced without affecting the complex identity of the cell. The rapidity of the change is measured by the *stability span* of C at *t*: it is the longest period *dt* such that C exists and admits a lower order decomposition which maintains its working conditions from *t* to *t*+*dt* not included (Ehresmann & Vanbremeersch, 1987). In particular the stability span of the cell has a magnitude order greater than that of its molecules, looked at separately.

Among the links from C to another component C', there are *n-simple links* which bind together a cluster of links between decompositions P of C and P' of C' of levels $\leq n$. These links just reflect properties already observable through lower level components of C and C'. However, there may also exist more *'complex'* links which 'emerge' at level n+1 thanks to the following characteristic of MES, explained below.

3.1.3 The Multiplicity Principle

The Multiplicity Principle, MP (Ehresmann & Vanbremeersch, 1996) models a kind of *flexible redundancy*, also called *degeneracy* in biology where it is

> " a ubiquitous biological property […] a feature of complexity […], both necessary for, and an inevitable outcome of, natural selection." (Edelman & Gally, 2001)

Formally MP asserts the existence of *multiform components* C which can operate, simultaneously or not, as aggregates of several lower level patterns P and Q possibly structurally non-equivalent and not connected by a cluster; and C can switch between them. Such switches will give robustness and flexibility to the system, in particular by allowing the formation of *n-complex links* which are composites of n-simple links binding non adjacent clusters. Though depending on the global structure of the levels $\leq n$, these links are not observable locally at these levels; they display properties emerging at the level $n+1$.

3.1.4 MP at the Root of Complexity

The level of a component C does not always reflect its 'real' complexity, which would correspond to the least number of binding processes necessary for re-constructing C from level 0 up (to be compared with Kolmogoroff-Chaitin 'complexity').

For that, we define the c*omplexity order* of C as the least length of a ramification down to level 0, a *ramification* being obtained by taking a lower level decomposition of C, then a lower level decomposition of each component P_i of P, and so on, down to components of level 0. A main theoretical result of this definition is the following

COMPLEXITY THEOREM (Ehresmann & Vanbremeersch, 1996). *MP is necessary for the existence of components of complexity order* > 1.

If MP is not satisfied, every component would be the aggregate of a pattern of components of level 0, as in a *pure reductionism.*

3.1.5 Complexification

The change of configuration from t to t' is due to operations of the following kinds: destruction of some components, decomposition of some complex components, addition of components, in particular by formation of a new component becoming the aggregate of an already existing pattern of linked components. It is modelled by the *complexification process* with respect to a *procedure* S having such objectives.

The complexification $K_{t'}$ of K_t with respect to S is explicitly constructed (Ehresmann & Vanbremeersch, 1987). It could be computed using the MGS language (Giavitto & Sprecher, 2008).

EMERGENCE THEOREM. *MP is preserved by iterated complexifications. It is necessary for the emergence over time of components of increasing complexity order. Moreover it intermingles the Aristotelian material, formal and efficient causes of the transitions.*

It follows that MP is a characteristic distinguishing "organisms" (such as MES) from "mechanisms" in the terms of (Rosen, 1985).

Remark. A procedure S can be interpreted as specifying a change of logic, which the complexification implements. Indeed, S leads to the construction of a mixed sketch, admitting the complexification as its prototype (constructed by A. & C. Ehresmann, 1972). Now it is known (Duval & Lair, 2002) that a mixed sketch can be interpreted as the diagrammatic presentation of a type of structure axiomatisable by a second order logic and the complexification gives a model of the corresponding theory. It can also be interpreted as the oriented object specification of an abstract type of data, thus opening the way for the complexification to be 'computable'.

3.2 Multi-scale Self-organisation of a MES and the Dynamics it Generates

The dynamics of a MES is modulated by the competition/cooperation between a heterarchical net of specialized functionally evolutive subsystems, the *co-regulators* (CRs). Each co-regulator has its own complexity, rhythm, logic, and a differential access to a central long-term *memory* which develops by learning and has robustness, flexibility and plasticity thanks to MP. The global logic/semantics of the system results from an interplay among the local logics/semantics of these co-regulators. The local constraints not respected by the resulting logic should be repaired later, perhaps causing cascades of events backfiring between levels.

3.2.1 One Step of a Co-Regulator (CR)

A Co-Regulator (CR) operates locally as a hybrid system, by a stepwise process at its own discrete timescale, one step extending between 2 successive instants of this timescale. The step decomposes in several more or less overlapping phases:

i. Formation of its *landscape at moment t* (modelled by a category L_t) with the partial incoming and/or remembered information transmitted to CR by active links.
ii. Selection (with the help of the memory) of a procedure S to respond (it should lead to the complexification AL of L_t by S).
iii. Sending commands to the effectors to realize S. It starts a dynamic process which unfolds during the continuous time of the step, possibly computable by differential equations, implicating the propagation delays and strengths of the links.
iv. The result is evaluated at the beginning *t'* of the next step by comparing AL to the new landscape. There is a *fractu*re for CR if the step is interrupted, or if the objectives of S are not met.

3.2.2 Temporal Constraints: The Synchronicity Laws

The step duration of CR beginning at moment *t* must be long enough so that CR may form its landscape, select a procedure S and send its commands to effectors. And during this time, the components in the landscape must preserve their overall internal organization up to the end of the step, in spite of the turnover of their lower order components. It follows that CR must respect the temporal constraints expressed by the following *Synchronicity Law*:

$$p(t) << d(t) << z(t)$$

where $p(t)$ is the mean propagation delay of the links intervening in the landscape at *t* and the commands of the procedure, $d(t)$ is the period of CR at *t* (= mean length of its close by preceding steps), and $z(t)$ is the smallest stability span of the components intervening in the landscape and the procedure (where “<<” means "of an order of magnitude lesser than").

The non-respect of one of these constraints is a main cause of dysfunction. A fracture not repaired soon enough causes a *dyschrony* of CR, and, if it persists, its repair may necessitate a change of period of CR, called *re-synchronization*.

3.2.3 The Interplay among Co-regulators

At the base of a MES, there is the "objective" continuous clock-time which helps coordinating the operations of the whole system. At a time *t*, the commands sent to effectors by the different co-regulators can be conflicting. Hence, there is a need of an equilibration process between them, possibly neglecting some of them.

This process, called the *interplay among the co-regulators*, leads to specify the operative procedure S° which will be really implemented on the system.

The interplay can take benefit of the degree of freedom given by the multiform components intervening in the various procedures; indeed they can operate through anyone of their lower level decompositions, with possible switches between them, allowing for a kind of selection to find the one most compatible with the other constraints.

Quantum processes can also have a role in this selection; it has been shown (Ehresmann & Vanbremeersch, 2002) that the existence of multiform components in biological systems takes its root in quantum processes occurring at the atomic level, and is extended to higher levels through successive complexifications.

3.2.4 Cascades of Dysfunction/Repair: Conclusion

The global logic specified by S° is a 'best compromise' between the different local logics specified by the various co-regulators; however it will cause more or less severe dysfunction to a co-regulator if its objectives are not realized, or if its synchronicity law cannot be respected.

A dysfunction of a co-regulator can backfire to others, with possibly severe consequences, such as loops of fracture/repair, possibly leading to the re-synchronisation of some co-regulator; or even a cascade of dysfunctions, itself leading to a cascade of re-synchronizations at various levels to avoid a "systemic disease".

Let us indicate some applications:

i. A physiologically inspired *Theory of aging* for a biological or a social organism through a cascade of re-synchronizations of co-regulators of increasing complexity (Ehresmann & Vanbremeersch, 1993).
ii. Efficient methods for ubiquitous complex events processing, in particular some methodology for anticipation in social systems such as large organizations, using switches between different realizations of multiform objects to generate complex scenarios.
iii. A main application is the model MENS for a neuro-cognitive-mental system (cf. Ehresmann, 2012, in this volume).

MES is a methodology in progress, still more qualitative than quantitative, and probably not amenable to 'usual' computations. This is where the idea for WLIMES, the Wandering LIMES (WLI + MES), project came from.

4 Can We Merge WLI and MES?

4.1 A Comparison of WLI and MES

WLI in is an evolving network architecture which is composed of dynamically reconfigurable network elements (netbots) which are generating and exchanging information about themselves and their surrounding environment (close neighborhood or 'local landscape') by means of active packets (shuttles) containing data and executable code for them. Shuttles are transporting various kinds of information (physical, algorithmic, topological, etc.).

A special kind of such local landscape information is the one about the formation of semi-stable patterns (spatial-temporal organization of entities and cyclic processes) incl. their discovery and communication mechanisms.

Co-regulators (CRs) in MES correspond to specialized subsystems of elements which are not necessarily disjoint, i.e. an element can belong to multiple CRs. Thus, CRs correspond to different (virtual) levels of structural and/or functional organization of the netbots. This organization is defined by the internal computation processes inside the netbot and by their external information delivered through the arriving shuttles.

While the components form an explicit hierarchy in MES, the CRs don't form a real hierarchy; their level comes from the level of their components, but a CR whose components are of level *n* does not aggregate CRs of lower levels. Netbots do not exhibit an explicit hierarchy. It is their landscapes at a given time which demonstrates a temporarily available internal composite hierarchy of structures and functions of their building elements interlinked with other elements and groups of them, in particular elements inside remote netbots. This composite hierarchy is changed stepwise (at the timescale of the CR) by that outcome of processing the shuttle information in combination with other internal and external exchange within the individual netbots and other components of the system. Herewith, the four WLI principles define the overall development of the network infrastructure.

The temporal and apparently undeterministic hierarchy of building different kinds of components, in particular elements inside the netbots and groups of them is guided by the 5th WLI principle, the Resource Usage and Availability Principle (RUA, cf. section 2.2.5), encouraging the development of stable structural-functional patterns of organization within and among the netbots. There might be different implementations of this principle such as differential logical distribution (Wepiwé, & Simeonov, 2005-2006). In P2P networks all the netbots are considered equivalent, unless a mechanism such as the Resource Usage and Availability Principle establishes a priority hierarchy. Some of them can have a biological character. In particular, in MES representing living systems, each CR has its own biological function.

Thus, the WLI architecture is complementary to a MES one. In a WLI, the mode of operation of the individual network elements (netbots) and their physical or virtual components depends on their processing/computation and on the result of interpretation/execution of the information/code contained in the arriving shuttles.

The transitions between netbots and their constituents execute a double function. On the one hand they illustrate such operations as addition, loss and binding of functional components inside a WLI closure or (sub)network. On the other hand, they represent unidirectional or bidirectional channels along which shuffles are transported. In MES, the links correspond to unique directed channels between the different components, which can be inter-levels (up or down) or intra-levels. The latter were implied in WLI in connection with the transmission of different types of shuttles.

One of the differences is that in MES there are also components (for instance in the memory, but not only there) which don't belong to CRs. The operations of a CR, such as the formation of its landscape, must also account for these other components. This is not the case with WLI yet.

The WN suggests a dynamic hierarchy within its multiple closures/(sub)networks. The netbots are cooperative; they negotiate their interplay/communication. They could be regarded as CRs in an emerging/development stage. Once the established channels between functional components/netbots become more frequently used, they can build semi-stable and permanent CRs and higher levels structural patterns of them. Hence, the CRs of a MES correspond to netbots or (virtual) clusters of them operating as units and always participating a WLI (sub)network; however the CRs are competitive and can be conflicting.

The reverse process is also possible. A WLI cluster/node can cease to operate/exist as a result of the interpretation/processing the information contained in incoming shuttles. Thus, a degradation/'aging' and even death of some parts of the wandering network is possible, thus enabling their replacement with new functional structures and links/channels between them. In the same manner operates the regeneration of same former dead areas of the network, once they involve living components, i.e. those at the edges of the network which maintain at least one connection to another netbot and capable to process its shuttles. The realization of such repair mechanisms depends on the particular 'regeneration' policies; the latter are matter of future investigation. In a MES both components and CRs may disappear either completely or through replacement by others, and new ones can be created (by aggregation of patterns) through the complexification process.

The memory in MES is centralized, with each CR having its own differential access to it, whereas in WLI it is distributed among the netbots, their components and the exchanged shuttles.

WLI's first duality principle suggests a duality between shuttles and netbots at the "arrival time" which means that the internal configuration/architecture and functionality of the netbot before the arrival of the shuttle changes in that manner after its arrival that it matches the structural and functional configuration (executable code) of the arriving shuttle after processing its information content. In other words, the shuttle causes changes in the netbot.

To which extent these changes result from evaluating and considering previous accumulation of such shuttle information and/or triggering/switching, integration/superposition or exclusion/differentiation between different types of signals, is left to the particular implementation of the mode of operation (operational semantics) of the WLI. This includes the selection of and the interplay between the 4+1 WLI principles.

In MES, there is a kind of duality between the situation at the beginning *t* and at the end *t'* of a step of the CR, caused by the information gathered in the landscape at *t* (through incoming 'shuttles'), and the selection of a procedure to respond by the CR.

On the other hand, the netbot also causes changes in the shuttle while processing it, thus influencing changes in other netbots receiving that shuttle at a later moment. This can be regarded as another incarnation of the dualistic congruence principle. In MES, the commands of the procedure selected by a CR transmit information (through 'shuttles') to other CRs, for instance to effector CRs such as the effectors of a 'muscular' command.

In summary, a WLI realization implies a multiplicity of evolving gates which operate in a highly undeterministic way. By definition the WLI nodes/gates cooperate to enable a self-stabilizing network architecture. However, they can also compete for some resource/function by involving some special reservation policies that can be transmitted by means of shuttles

The intelligence/plasticity of the system at the moment *t* is the instant result/response of the interplay between its constituting elements (components, netbots and interworking clusters of them). In MES the interplay is through the procedures of the different CRs at a given time, and its flexibility comes from the multiplicity principle allowing to process each command along its most adapted ramification.

4.2 Complementarities between MES and WLI

We found the following complementarities between our approaches.

(i) **Patterns.** CRs are initially defined as patterns of components; these patterns may bind ('aggregate') into high-level components, but it is not always the case. The reachability tree of the netbot corresponds to its abstract connectivity landscape (localization). A netbot's 'landscape' at a moment *t* contains only the connectivity/links active at this moment. In WLI information about this abstract landscape is spread out by means of shuttles; in MES the case is different, because the categories vary over time. The new information can be 'seen' through the transition functors by looking to what is new and what gets lost. A CR uses the information at a moment *t* by the fact that it is 'here'. This difference comes out of the fact that WLI is a system which varies, while MES is described by the family of its successive configurations, and the 'transitions' between them. The formation and recognition of structural spatio-temporal organization patterns in WLI is operational; it is part of the specific implementation which can be realized e.g. by labeled shuttles carrying archetypal n-genes, r-genes and t-genes to be identified in the processing netbots.

(ii) **Rhythms.** In MES each CR has its own rhythm; the interplay among the temporalities of different CRs has an important role in the interplay among CRs, for instance leading to a 'dialectics' between CRs of different complexity and short/long period; it is also important for the mechanisms of failure/repair which may backfire between CRs. It is not clear yet how such rhythms can be implemented in WLI.

(iii) **Distributed vs. Centralized Memory.** The memory in WLI is distributed inside the netbots and shuttles, while in MES there is a central memory to which each CR has a differential access. The distributed nature of the memory in WLI is operative, allowing the fast propagation of local and non-local system changes, whereas the centralized one in MES is both robust and flexible, allowing for adaptation to changing environmental conditions. .

(iv) **Hierarchy.** In MES the hierarchy is exquisitely described: a high-level component binding at least one pattern of lower ones. This allows the existence of multiform components (MP). In WLI the hierarchy is implicitly described by entailment relations between the building components inside the netbots and outside of them with other components in other netbots in terms of virtual closures/overlays. This is the mechanism in which a single netbot component can participate in different network overlay configurations. In MES this hierarchy concerns all the components. The CRs are sub-systems which inherit the complexity of their components, but they don't form a strict hierarchy. A higher CR may control different lower CRs, but not always and not strictly, depending on the MES.

(v) **Link Activation.** One of the problems with MES is that there is no explanation of how links are 'activated' at a given time/event (except for MENS). Therefore, we are intending to use shuttles representing information carried out by the links when they become activated. Shuttles are particularly interesting in 3 cases regarding the operational semantics of MES:

1. In the formation of the landscape of a CR at moment *t*: only the perspectives for the CR of links activated by a shuttle arriving about the moment *t* are retained in the landscape;
2. In the selection of a procedure, either by a CR or in the interplay among CRs, where the respective strengths of the payloads of the shuttles activating different admissible procedures (coming from the memory) will play a role.
3. In the commands of a procedure to its effectors, in particular during the interplay among CRs to form an operating procedure. Thus, shuffles will be at the base of the 'progressive' dynamics in MES.

(vi) **WLI Principles.**

1. The 'duality principle' of WLI reduces to a 'partial duality' in MES: on the one hand, the construction of the landscape of a CR at moment *t*, and the selection of its procedure depend on the information received by the CR through the shuttles which it ‘unpacks’; on the other hand, the realization of this procedure consists in 'packing' into shuttles the commands of the procedure to effector CRs.
2. The 'self reference' principle in WLI relates to the autonomy/autopoiesis, also valid for MES. However, in WLI it supposes that netbots always cooperate,

whereas in MES there is a possibility of conflicts between CRs which are at the basis of the interplay among CRs, thus allowing for the ubiquity, plasticity though robustness (and non predictability) of MES. As stated above, it is possible to develop mechanisms in WLI used by shuttles that stimulate competition among CRs. Thus, both policies, cooperation and competition among CRs, become possible.

3. The 'multiple dimensions' principle in WLI would be stronger in MES, since we have the various temporalities of the CRs and their differing logics (hence, the risk of competition and fractures). Furthermore, the development of the memory by learning/experience plays an essential role in MES, in particular in more complex MES (e.g. the application MENS to a neuro-cognitive system) where a sub-system called the *Archetypal Core* can develop to function out as an internal model of the system/self. This operational semantics can be also developed in terms of specific WLI implementations.
4. The 'pulsating metamorphosis' principle in WLI was initially related to the possibility of upscaling and downscaling the wandering network in terms of functional-structural elements (shuttles, netbots, their components and clusters). It could correspond to the double dynamics in MES: local (via CRs) vs. global (via their interplay). This appears to be also in relation with the development and use of memory. A further elaboration of the details of this principle in the MES context is necessary to optimally capture and exploit the synergies between WLI and MES. TLA (Lamport, 1994), which is the implementation base of WLI, combines the logic of actions with a temporal logic. It seems to be suitable to represent the 'hybridity' or dual nature of the CRs using: a) the logic of actions via commands of procedures, and b) a temporal logic via their realization during the next step of their effector CRs. Then the interplay among CRs adds a global logic on top of the different interacting temporalities and local logics. This model is implied in WLI for higher levels of organization of the wandering network (e.g. self-reflecting and 'conscious' networks), but not explicitly stated. Therefore, the specific realization in terms of MES needs to be further elaborated.
5. The 'resource usage and availability' principle in WLI is a guidance directive for the formation of semi-stable and permanent network configurations based on the modes of their exploitation. It could have a number of implementations, incl. e.g. the realization of specific policies for competition among CRs transported by 'marked' shuttles. The particular application of this principle in MES context should be further investigated.

(vii) **MES Principles.**

1. The 'Multiplicity/degeneracy Principle' (MP) in MES which ensures that different patterns, possibly not structurally equivalent nor even well connected, can be functionally equivalent. As explained in Section 3.2 it is at the root of the emergence of higher complexity, robustness and flexibility.
2. The 'synchronicity laws' which must be respected by each co-regulator, at the root of ubiquitous complex events (cf. Section 3.2.2)

(vii) **Safety and Liveness.** These properties are important in the context of computing and networking systems to guarantee their robustness in case of failures. They were essential for the original WLI application domain. However, in multi-scale complex systems modeled in MES, there is both the risk of fractures and the possibility of developing repair mechanisms (e.g. by re-synchronization of some CRs).

It is not yet clear how to embed the safety and liveness properties in biological context. Further investigations are required to answer this question.

5 Conclusions and Outlook

This analysis shows that WLI and MES present important complementarities:

WLI

- provides a formal means for the specification and verification of the generic temporal properties of netbots and shuttles;
- supports the reflexive dynamic adaptation of both mobile code (software) and node architecture (software and hardware);
- provides the formal means for specification and verification of dynamic properties in ad-hoc mobile networks;
- assists the formal transformation of the systems' properties into mobile code.

These capabilities allow the WLI usage in modeling the operational semantics of complex biosyntheic systems.

MES proposes a developing methodology in a well-structured frame emphasizing important properties of multi-scale, and multi-agent multi-temporality systems (Multiplicity Principle, Synchronicity Laws) at the basis of the emergence of complexity, self-repair, learning and adaptation; however it remains mostly qualitative.

Our WLIMES project proposes to develop a theoretical frame englobing these two theories, so that each one benefits from the stronger aspects of the other. The target would be to obtain a dynamic model for complex systems, in particular for living systems, demonstrating most properties of both systems, and accessible to some kind of 'computation'.

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