Dynamic Complexity of Autonomic Communication and Software Systems

Andrei Kirilyuk[1] and Mikaël Salaün[2]

[1] National Academy of Sciences of Ukraine, Institute of Metal Physics
36 Vernadsky Ave, 03142 Kiev-142, Ukraine
kiril@metfiz.freenet.kiev.ua
[2] France Télécom, Division R&D/MAPS/MMC/LAN
38-40 rue du Général Leclerc, 92794 Issy-les-Moulineaux Cedex 9, France
mikael.salaun@francetelecom.com

Dynamics of arbitrary communication and software system is analysed as unreduced interaction process. The applied generalised, universally nonperturbative method of effective potential reveals the phenomenon of dynamic multivaluedness of competing system configurations forced to permanently replace each other in a dynamically random order, which leads to universally defined dynamical chaos, complexity, fractality, self-organisation, and adaptability. We demonstrate the origin of the huge, exponentially high efficiency of the unreduced, complex network and software dynamics and specify the universal symmetry of complexity as the fundamental guiding principle for creation and control of such qualitatively new kind of network and software systems. Practical aspects of ICT complexity transition are outlined.

1 Introduction

Any communication and software system can be considered as a dynamical system formed by many interacting units. If system components can interact without *strict* external control (which is a rapidly growing tendency of modern ICT tools), then such *unreduced* interaction process leads to *complex-dynamical*, essentially *nonlinear* and *chaotic* structure emergence, or (*dynamically multivalued*) self-organisation [1–3], extending usual, regular self-organisation concept. Traditional information technologies and paradigm rely, however, on very strong human control and totally regular, predictable dynamics of controlled systems and environment, where unpredictable elements can only take the form of undesirable system failure or noise.

Growing sophistication of communication and software systems leads to dangerously rising probability of undesirable deviations from pre-programmed regular behaviour, thus largely compromising its expected advantages. On the other hand, such increasingly attractive system properties as intrinsic creativity and autonomous adaptability to changing environment and individual user demands should certainly involve another, much less regular and more diverse kind of

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behaviour. In this paper we analyse these issues in a rigorous way by presenting the unreduced, nonperturbative analysis of arbitrary system of interacting communication and software units and show that such *unreduced interaction process* has the natural, dynamically derived properties of chaoticity, creativity (autonomous structure formation ability), adaptability, and exponentially high efficiency, which are consistently unified in the *universal* concept of *dynamic complexity* [1]. This concept and particular notions it unifies represent essential extension with respect to usual theory results always using one or another version of perturbation theory that strongly reduces real interaction processes and leads inevitably to regular kind of dynamics (even in its versions of "chaoticity"). We shall specify those differences in our analysis and demonstrate the key role of unreduced, interaction-driven complexity, chaoticity and self-organisation in the superior operation properties, as it has already been demonstrated for a large scope of applications [1–10].

The proposed universal theory of autonomic information system correlates positively with other emerging, usually empirically based approaches to growing sophistication of communication networks and software systems. One may evoke various recent research initiatives on "pervasive computing", "ambient intelligence", "autonomic communication networks", "knowledge-based networks", "context awareness", "semantic grid/web", "complex software", etc. (see e.g. [11–16] for representative overview sources and multiple further references). By providing the unambiguous, rigorously derived, reality-based and universally applicable definition of dynamic complexity and classification of possible dynamic regimes in *any* communication and software system, our theory can play the role of indispensable *unifying basis* for further research and applications, revealing existing possibilities for each particular case. Approximation of a real system dynamics by a simulative or metaphorical (mechanistic) "complexity" remains feasible, but now one can consistently estimate its validity, pertinence, losses and advantages.

We start, in Section 2, with a mathematical demonstration of the fact that the unreduced interaction process within *any* real system leads to *intrinsic*, genuine and omnipresent *randomness* in system behaviour realised in a few regimes and summarised by the *universally* defined *dynamic complexity*. We outline the change in strategy and practice of communication and software system construction and use, which follows from such unreduced analysis of system interactions. *Universality* of our analysis is of special importance here, since the results can be applied at various *naturally entangled* levels of ICT system operation, including e.g. autonomic communication network, related software clients, and human/environment components. We demonstrate the origin of huge, *exponentially high efficiency growth* of unreduced, causally random system dynamics with respect to usual, regular system operation (Section 3). Finally, the dynamically derived, *universal symmetry, or conservation, of complexity* is introduced as the new *guiding principle* and tool of complex system design extending usual, regular programming. The *paradigm of intelligent (complex-dynamic) communication and software systems* is thus specified, since we show also [1,5,6] that the property of *intelligence* can be consistently described as high enough levels of unreduced dynamic complexity. That *intelligent ICT* framework based on unreduced interaction complexity is the most complete realisation, and in fact unifying synonym, of *truly autonomous*, user-oriented and knowledge-based communication dynamics (Section 4).

2 Complex dynamics of unreduced interaction process

We begin with a general expression of multi-component system dynamics (or many-body problem) called here *existence equation*, fixing the fact of interaction between the system components, and generalising various model equations:

$$\left\{\sum_{k=0}^{N}\left[h_k(q_k)+\sum_{l>k}^{N}V_{kl}(q_k,q_l)\right]\right\}\Psi(Q)=E\Psi(Q)\ , \tag{1}$$

where $h_k(q_k)$ is the "generalised Hamiltonian" for the k-th system component in the absence of interaction, q_k is the degree(s) of freedom of the k-th component (expressing its "physical nature"), $V_{kl}(q_k,q_l)$ is the (generally arbitrary) interaction potential between the k-th and l-th components, $\Psi(Q)$ is the system state-function, $Q\equiv\{q_0,q_1,...,q_N\}$, E is the eigenvalue of the generalised Hamiltonian, and summations are performed over all (N) system components. The generalised Hamiltonian, eigenvalues, and interaction potential represent a suitable measure of dynamic complexity defined below and encompassing practically all "measurable" quantities (action, energy, momentum, current, etc.) at any level of dynamics. Therefore (1) can express unreduced interaction configuration at any level of arbitrary communication network. It can also be presented in a particular form of time-dependent equation by replacing the generalised Hamiltonian eigenvalue E with the partial time derivative operator (for the case of explicit interaction potential dependence on time).

One can separate one of the degrees of freedom, e.g. $q_0\equiv\xi$, corresponding to a naturally selected, usually "system-wide" entity, such as "embedding" configuration (system of coordinates) or common "transmitting agent":

$$\left\{h_0(\xi)+\sum_{k=1}^{N}\left[h_k(q_k)+V_{0k}(\xi,q_k)+\sum_{l>k}^{N}V_{kl}(q_k,q_l)\right]\right\}\Psi(\xi,Q)=E\Psi(\xi,Q)\,, \tag{2}$$

where now $Q\equiv\{q_1,...,q_N\}$ and $k,l\geq 1$.

We then express the problem in terms of known free-component solutions for the "functional", internal degrees of freedom of system elements ($k\geq 1$):

$$h_k(q_k)\,\varphi_{kn_k}(q_k)=\varepsilon_{n_k}\varphi_{kn_k}(q_k)\ , \tag{3}$$

$$\Psi(\xi,Q)=\sum_n\psi_n(\xi)\varphi_{1n_1}(q_1)\,\varphi_{2n_2}(q_2)\ldots\varphi_{Nn_N}(q_N)\equiv\sum_n\psi_n(\xi)\Phi_n(Q)\,, \tag{4}$$

where $\{\varepsilon_{n_k}\}$ are the eigenvalues and $\{\varphi_{kn_k}(q_k)\}$ eigenfunctions of the k-th component Hamiltonian $h_k(q_k)$, forming the complete set of orthonormal functions, $n \equiv \{n_1, ..., n_N\}$ runs through all possible eigenstate combinations, and $\Phi_n(Q) \equiv \varphi_{1n_1}(q_1)\varphi_{2n_2}(q_2)...\varphi_{Nn_N}(q_N)$ by definition. The system of equations for $\{\psi_n(\xi)\}$ is obtained then in a standard way, using the eigen-solution orthonormality (e.g. by multiplication by $\Phi_n^*(Q)$ and integration over Q):

$$[h_0(\xi) + V_{00}(\xi)]\psi_0(\xi) + \sum_n V_{0n}(\xi)\psi_n(\xi) = \eta\psi_0(\xi)$$
$$[h_0(\xi) + V_{nn}(\xi)]\psi_n(\xi) + \sum_{n' \neq n} V_{nn'}(\xi)\psi_{n'}(\xi) = \eta_n\psi_n(\xi) - V_{n0}(\xi)\psi_0(\xi), \tag{5}$$

where $n, n' \neq 0$ (also below), $\eta \equiv \eta_0 = E - \varepsilon_0$, $\eta_n = E - \varepsilon_n$, $\varepsilon_n = \sum_k \varepsilon_{n_k}$,

$$V_{nn'}(\xi) = \sum_k \left[V_{k0}^{nn'}(\xi) + \sum_{l>k} V_{kl}^{nn'} \right], \tag{6}$$

$$V_{k0}^{nn'}(\xi) = \int_{\Omega_Q} dQ\Phi_n^*(Q)V_{k0}(q_k, \xi)\Phi_{n'}(Q) , \tag{7}$$

$$V_{kl}^{nn'}(\xi) = \int_{\Omega_Q} dQ\Phi_n^*(Q)V_{kl}(q_k, q_l)\Phi_{n'}(Q) , \tag{8}$$

and we have separated the equation for $\psi_0(\xi)$ describing the generalised "ground state", i. e. the state with minimum complexity. The obtained system of equations expresses the same problem as the starting equation (2), but now in terms of "natural", dynamic variables, and therefore it can be obtained for various starting models, including time-dependent and formally "nonlinear" ones (see below for a rigorous definition of *essential* nonlinearity).

We try now to approach a "nonintegrable" system of equations (5) with the help of generalised effective, or optical, potential method [17], where one expresses $\psi_n(\xi)$ through $\psi_0(\xi)$ from the equations for $\psi_n(\xi)$ using the standard Green function technique and then substitutes the result into the equation for $\psi_0(\xi)$, obtaining thus the *effective existence equation* that contains *explicitly* only "integrable" degrees of freedom (ξ) [1–5, 8–10]:

$$h_0(\xi)\psi_0(\xi) + V_{\text{eff}}(\xi;\eta)\psi_0(\xi) = \eta\psi_0(\xi) , \tag{9}$$

where the operator of *effective potential (EP)*, $V_{\text{eff}}(\xi;\eta)$, is given by

$$V_{\text{eff}}(\xi;\eta) = V_{00}(\xi) + \hat{V}(\xi;\eta), \quad \hat{V}(\xi;\eta)\psi_0(\xi) = \int_{\Omega_\xi} d\xi' V(\xi,\xi';\eta)\psi_0(\xi'), \tag{10}$$

$$V(\xi,\xi';\eta) = \sum_{n,i} \frac{V_{0n}(\xi)\psi_{ni}^0(\xi)V_{n0}(\xi')\psi_{ni}^{0*}(\xi')}{\eta - \eta_{ni}^0 - \varepsilon_{n0}} , \quad \varepsilon_{n0} \equiv \varepsilon_n - \varepsilon_0 , \tag{11}$$

and $\{\psi_{ni}^{0}(\xi)\}$, $\{\eta_{ni}^{0}\}$ are complete sets of eigenfunctions and eigenvalues of a *truncated* system of equations:

$$[h_0(\xi) + V_{nn}(\xi)]\,\psi_n(\xi) + \sum_{n' \neq n} V_{nn'}(\xi)\psi_{n'}(\xi) = \eta_n \psi_n(\xi) \ . \qquad (12)$$

One can use now the eigenfunctions, $\{\psi_{0i}(\xi)\}$, and eigenvalues, $\{\eta_i\}$, of a formally "integrable" equation (9) to obtain other state-function components:

$$\psi_{ni}(\xi) = \hat{g}_{ni}(\xi)\,\psi_{0i}(\xi) \equiv \int\limits_{\Omega_\xi} d\xi' g_{ni}(\xi,\xi')\,\psi_{0i}(\xi') \ , \qquad (13)$$

$$g_{ni}(\xi,\xi') = V_{n0}(\xi') \sum_{i'} \frac{\psi_{ni'}^{0}(\xi)\,\psi_{ni'}^{0*}(\xi')}{\eta_i - \eta_{ni'}^{0} - \varepsilon_{n0}} \ , \qquad (14)$$

and the total system state-function, $\Psi(q_0, q_1, ..., q_N) = \Psi(\xi, Q)$ (see (4)):

$$\Psi(\xi, Q) = \sum_i c_i \left[\Phi_0(Q) + \sum_n \Phi_n(Q)\,\hat{g}_{ni}(\xi) \right] \psi_{0i}(\xi) \ , \qquad (15)$$

where coefficients c_i should be found from the state-function matching conditions at the boundary where interaction effectively vanishes. The measured quantity, generalised system density $\rho(\xi, Q)$, is obtained as state-function squared modulus, $\rho(\xi, Q) = |\Psi(\xi, Q)|^2$ (for "wave-like" complexity levels), or as state-function itself, $\rho(\xi, Q) = \Psi(\xi, Q)$ (for "particle-like" structures) [1].

Since EP expression in the effective problem formulation (9)–(11) depends essentially on the eigen-solutions to be found, the problem remains "nonintegrable" and equivalent to its initial formulation (1), (2), (5). However, it is the effective version of a problem that leads to its unreduced solution and reveals the nontrivial properties of the latter [1–10]. The key property of unreduced interaction result (9)–(15) is its *dynamic multivaluedness* meaning that one has a *redundant* number of individually complete and therefore *mutually incompatible* solutions describing *equally real* system configurations. We call each such locally complete solution (and real system configuration) *realisation* of the system and problem. Realisation plurality follows from unreduced EP expressions due to nonlinear and self-consistent dependence on the solutions to be found, reflecting physically real and evident plurality of interacting eigen-mode combinations [1–10]. It is important that dynamic multivaluedness emerges only in the unreduced problem formulation, whereas a standard theory, including EP application (see e.g. [17]) and scholar "science of complexity" (theory of chaos, self-organisation, etc.), resorts invariably to one or another version of perturbation theory, whose approximation, used to obtain an "exact", closed-form solution, just "kills" *redundant* solutions by eliminating *dynamically* emerging nonlinear links and retains *only one*, "averaged" solution, usually expressing but *small* deviations from initial system configuration. That *dynamically single-valued*, or *unitary*, problem reduction forms the basis of the whole canonical science paradigm.

Since we have many *incompatible* system realisations explicitly appearing from the same, driving interaction, we obtain a major property of *causal, or dynamic, randomness* in the form of permanently *changing* realisations that replace each other in a *truly random* (unpredictable, undecidable, noncomputable) order. Therefore dynamic multivaluedness, rigorously derived simply by unreduced, correct solution of a real many-body (interaction) problem, provides the *universal dynamic origin* and *meaning* of *omnipresent, unceasing* randomness in system behaviour, also called *(dynamical) chaos* (it is essentially different from any its unitary version, reduced to "involved regularity" or *incorrectly postulated* "noise amplification"). It means that the truly complete *general solution* of arbitrary problem (describing a *real* system behaviour) has the form of *dynamically probabilistic* sum of measured quantities for different realisations:

$$\rho(\xi, Q) = \sum_{r=1}^{N_{\Re}}{}^{\oplus} \rho_r(\xi, Q) \ , \tag{16}$$

where summation is performed over all system realisations, $N_{\Re}$ is their number (its maximum value is equal to the number of system components, $N_{\Re} = N$), and the sign $\oplus$ designates the special, dynamically probabilistic meaning of the sum described above. It implies that any measured quantity (16) is *intrinsically unstable* and its current value *will* unpredictably change to another one, corresponding to another, *randomly* chosen realisation. Such kind of behaviour is readily observed in nature and actually explains the living organism behaviour [1, 4, 5], but is avoided in unitary theory and usual technological (including ICT) systems, where it is correctly associated with linear "noncomputability" and technical failure (we shall consider below that *limiting* regime of real system dynamics). Therefore, universal dynamic multivaluedness thus revealed by rigorous problem solution forms a fundamental basis for transition to "bio-inspired" and "intelligent" kind of operation in artificial, especially ICT systems, where causal randomness can be transformed from an obstacle to qualitative advantage (Section 3).

The obtained causal randomness of generalised EP formalism (9)–(16) is accompanied by the *dynamic probability definition.* Since elementary realisations are equal in their "rights to appear", the dynamically derived, *a priori probability*, α_r, of elementary realisation emergence is given by

$$\alpha_r = \frac{1}{N_{\Re}} \ , \quad \sum_r \alpha_r = 1 \ . \tag{17}$$

However, actual observations may deal with dense groups of elementary realisations because of their multivalued self-organisation (see below). Therefore the dynamic probability of observation of such general, compound realisation is determined by the number, N_r, of elementary realisations it contains:

$$\alpha_r(N_r) = \frac{N_r}{N_{\Re}} \quad \left(N_r = 1, ..., N_{\Re}; \ \sum_r N_r = N_{\Re}\right) , \quad \sum_r \alpha_r = 1 \ . \tag{18}$$

An expression for *expectation value*, $\rho_{\exp}(\xi, Q)$, can easily be constructed from (16)–(18) for statistically large event numbers:

$$\rho_{\exp}(\xi, Q) = \sum_r \alpha_r \rho_r(\xi, Q) \ . \tag{19}$$

It is important, however, that our dynamically derived randomness and probability need not rely on such "statistical", empirically based definition and basic expressions (16)–(18) remain valid even for any *single* event of realisation emergence and *before* any event happens at all.

Realisation probability distribution can be obtained in another way, involving the *generalised wavefunction (or distribution function)* and *Born's probability rule* [1, 3, 5, 10, 18]. The wavefunction describes the system state during its transition between "regular", "concentrated" realisations and constitutes a particular, "intermediate", or "main" realisation with spatially extended and "loose" (chaotically changing) structure, where system components transiently disentangle before forming the next "regular" realisation. The generalised wavefunction is obtained in the unreduced EP formalism by *causal (dynamic) quantization* [1, 3, 5, 6, 10, 18] and provides, in particular, a totally realistic version of quantum-mechanical wavefunction at the lowest, "quantum" levels of complexity. The "Born probability rule", now also causally derived and extended to any level of world dynamics, states that realisation probability distribution is determined by wavefunction values (their squared modulus for "wave-like" complexity levels) for respective system configurations. The generalised wavefunction satisfies the universal Schrödinger equation (Section 3) rigorously derived by causal quantization, while Born's probability rule follows from the *dynamic* "matching conditions" mentioned in connection with the state-function expression (15) and actually satisfied during each system transition between a "regular" realisation and the extended wavefunction state. Note also that it is *only* that "averaged", weak-interaction state of the wavefunction, or "main" realisation, that remains in the dynamically single-valued, one-realisation "model" and "exact-solution" paradigm of unitary theory, which explains both its partial success and fundamental limitations.

Closely related to dynamic multivaluedness is the property of *dynamic entanglement* between interacting components, described in (15) by the dynamically weighted products of state-function components depending on different degrees of freedom (ξ, Q). It provides a *rigorous* expression of the tangible *quality* of emerging system structure and is absent in unitary models. The obtained *dynamically multivalued entanglement* describes a "living" structure permanently changing and probabilistically *adapting* its configuration, which provides a well-specified basis for "bio-inspired" technological solutions. The properties of dynamically multivalued entanglement and adaptability are further amplified due to complex-dynamic, *probabilistic fractality* of unreduced general solution [1, 4–6] obtained by application of the same EP method to solution of truncated system of equations (12) involved in the first-level EP expression (11).

We can now consistently and *universally* define the unreduced *dynamic complexity*, C, of *any* real system or interaction process as a growing function of the number of *explicitly obtained* system realisations, $C = C(N_{\Re})$, $dC/dN_{\Re} > 0$, or rate of their change, equal to zero for the unrealistic case of only one system realisation, $C(1) = 0$. Suitable examples are provided by $C(N_{\Re}) = C_0 \ln N_{\Re}$, generalised energy/mass (proportional to the temporal rate of realisation change), and momentum (proportional to the spatial rate of realisation emergence) [1, 5, 10, 18]. It becomes clear that the whole *dynamically single-valued* paradigm and results of canonical theory (including its versions of "complexity" and *imitations* of "multi-stability" in *abstract*, mathematical "spaces") correspond to exactly *zero* value of unreduced complexity equivalent to effectively zero-dimensional, point-like projection of reality.

Correspondingly, *any* dynamically single-valued "model" is strictly regular and *cannot* possess any true, intrinsic randomness (chaoticity), which should instead be introduced artificially (and inconsistently), e.g. as a *regular* "amplification" of "random" (by convention) *external* "noise" or "measurement error". By contrast, our unreduced dynamic complexity is practically synonymous to equally universally defined and genuine *chaoticity* (see above), since *multiple* system realisations, appearing and disappearing only in *real* space (and *forming* thus its tangible, changing structure [1, 3, 5, 10]), are *redundant (mutually incompatible)*, which is the origin of *both* complexity and chaoticity. Genuine dynamical chaos thus obtained has a complicated internal structure (contrary to ill-defined unitary "stochasticity") and contains *partial regularity* dynamically mixed with irregularity in *inhomogeneous* realisation *probability* distribution.

Universal dynamic complexity and related properties involve the *essential, or dynamic, nonlinearity* of unreduced problem solution. It is provided by feedback links of developing interaction as they are expressed by EP dependence on the problem solutions (see (9)–(11)). It is the *dynamically emerging* nonlinearity, since it appears even for a formally "linear" initial problem expression (1)–(2), (5), whereas usual, mechanistic "nonlinearity" is but a perturbative reduction of essential nonlinearity of unreduced EP expressions. Essential nonlinearity leads to irreducible *dynamic instability* of any system state (realisation): both are determined by the same mechanism of dynamic feedback development.

Universality of our description leads, in particular, to the unified understanding of the whole diversity of existing dynamical regimes and types of system behaviour [1, 2, 5]. One standard, limiting case of complex (multivalued) dynamics, called *uniform, or global, chaos*, is characterised by sufficiently different realisations with a homogeneous distribution of probabilities (i.e. $N_r \approx 1$ and $\alpha_r \approx 1/N_{\Re}$ for all r in (18)) and emerges when major parameters of interacting entities (suitably represented by frequencies) are similar to each other (which leads to a strong "conflict of interests" and resulting "big disorder"). The complementary limiting regime of *multivalued self-organisation, or self-organised criticality (SOC)* emerges for sufficiently different parameters of interacting components, so that a small number of relatively rigid, low-frequency components "enslave" a hierarchy of high-frequency and rapidly changing, but configurationally similar realisations (i.e. $N_r \sim N_{\Re}$ and realisation probability distribution is highly inhomogeneous). The difference of that extended, multivalued SOC from usual, unitary self-organisation is essential: despite the rigid *external* shape of system configuration in this regime, it contains an intense "internal life" and *chaos* of changing "enslaved" realisations (which are *not* superposable unitary "modes"). Another important advance with respect to unitary "science of complexity" is that the unreduced, multivalued self-organisation unifies extended versions of a whole series of separated unitary "models", including SOC, "synchronisation", "control of chaos", "attractors", and "mode locking". All intermediate dynamic regimes between the limiting cases of uniform chaos and multivalued SOC (as well as their multi-level, fractal combinations) are obtained for intermediate parameter values. The point of transition to strong chaos is expressed by the *universal criterion of global chaos onset*:

$$\kappa \equiv \frac{\Delta\eta_i}{\Delta\eta_n} = \frac{\omega_\xi}{\omega_q} \cong 1 \ , \tag{20}$$

where κ is the introduced *chaoticity* parameter, $\Delta\eta_i$, ω_ξ and $\Delta\eta_n \sim \Delta\varepsilon$, ω_q are energy-level separations and frequencies for the inter-component and intra-component motions, respectively. At $\kappa \ll 1$ one has the externally regular multivalued SOC regime, which degenerates into global chaos as κ grows from 0 to 1, and the maximum irregularity at $\kappa \approx 1$ is again transformed into a SOC kind of structure at $\kappa \gg 1$ (but with the "inverse" system configuration).

One can compare this transparent and universal picture with separated and incomplete unitary criteria of chaos and regularity. Only the former provides a real possibility of understanding and control of ICT systems of arbitrary complexity, where more regular regimes form a general direction of system dynamics, while less regular ones play the role of efficient search and adaptation means. That combination constitutes the basis of any "biological" and "intelligent" kind of behaviour [1, 4–7] and therefore determines the *intelligent ICT paradigm* supposed to extend the current practice of communication and software of (quasi-) regular limiting regime, $\kappa \to 0$. While the latter *inevitably* becomes inefficient with growing system sophistication (where chaos-bringing resonances of (20) *cannot* be avoided any more), it definitely lacks the "intelligent power" of unreduced complex dynamics to generate meaning and adaptable structure development.

3 Huge efficiency of unreduced interaction dynamics and the guiding role of the symmetry of complexity

Dynamically probabilistic fractality of system structure emerges naturally by the unreduced interaction development [1, 4–6]. It is obtained mathematically by application of the same EP method (9)–(14) to solution of truncated system of equations (12), then to solution of the next truncated system, etc., which gives the irregular and *probabilistically moving* hierarchy of realisations, containing an intermittent mixture of global chaos and multivalued SOC, which constitute together a sort of *confined chaos*. The total realisation number $N_{\Re}$, and thus the power, of that autonomously branching interaction process with a *dynamically parallel* structure grows *exponentially* with its volume [5].

Indeed, if our system of inter-connected elements contains N_{unit} "processing units", or "junctions", and if each of them has n_{conn} real or "virtual" (possible) links, then the total number of interaction links is $N = n_{\text{conn}} N_{\text{unit}}$. In most important cases N is a huge number: for both human brain and genome interactions N is greater than 10^{12}, and being much more variable for ICT systems, it will tend to similar "astronomical" ranges. The key property of *unreduced, complex* interaction dynamics, distinguishing it from any unitary "model", is that the maximum number $N_{\Re}$ of realisations taken by the system (also per time unit) and determining its real "power" P_{real} (of search, memory, cognition, etc.) is given by the number of *all possible combinations of links*, i.e.

$$P_{\text{real}} \propto N_{\Re} = N! \to \sqrt{2\pi N}\left(\frac{N}{e}\right)^{N} \sim N^{N} \ggg N \; . \tag{21}$$

Any unitary, sequential model of the same system (including its *mechanistically* "parallel" and "complex" modes) would give $P_{\text{reg}} \sim N^{\beta}$, with $\beta \sim 1$, so that

$$P_{\text{real}} \sim \left(P_{\text{reg}}\right)^{N} \ggg P_{\text{reg}} \sim N^{\beta} \; . \tag{22}$$

Thus, for $N \sim 10^{12}$ we have $P_{\text{real}} \gg 10^{10^{13}} \gg 10^{10^{12}} = 10^{N} \to \infty$, which is a "practical infinity", also with respect to the unitary power of $N^{\beta} \sim 10^{12}$.

These estimates demonstrate the true power of complex (multivalued) communication and software dynamics remaining suppressed in its unitary, quasi-regular operation mode dominating in modern technologies. Huge power values for complex-dynamical interaction correlate with emergence of new *qualities*, such as *autonomy (adaptability)*, *intelligence* and *consciousness* (at higher complexity levels) [5,6], in direct relation to our *intelligent* communication and software paradigm meaning that such properties as *sensible*, context-related information processing, personalised *understanding* and autonomous *creativity* (useful self-development), desired for next-generation ICT tools, are natural *qualitative* manifestations of the above "infinite" power.

Everything has a price, however, and a price to pay for the above huge power and qualitative advantages of complex-dynamic information-processing systems is rigorously specified now as irreducible *dynamic randomness* and thus unpredictability of their operation details. We only confirm here an evident conclusion that *autonomous* adaptability and genuine *creativity* exclude any regular, predictable pre-programming. But then what can serve as a guiding principle and practical strategy of design and control of complex communication networks and software tools? We show in our further analysis of unreduced interaction process that those guiding rules and strategy can be unified into a general law of complex (multivalued) dynamics, the *universal symmetry, or conservation, of complexity* [1,3,5,6]. That universal "order of nature" and evolution law unifies extended versions of all (correct) conservation laws, symmetries, and postulated "principles" (which are dynamically derived and realistically interpreted now). Contrary to any unitary symmetry, the universal symmetry of complexity is *irregular* in its structure, but always *exact* (never "broken"). Its "horizontal" manifestation (at a given level of complexity) implies actual, dynamic symmetry between realisations, which are really taken by the system and constitute thus its dynamics (and evolution) by contrast to usual abstract "symmetry operators". Therefore conservation, or symmetry, of system complexity totally determines its dynamics and explains the deep "equivalence" (link) between chaotically changing and often quite dissimilar realisation configurations.

Another, "vertical" manifestation of the universal symmetry of complexity is somewhat more involved and determines progressive emergence and development of different levels of complexity within a real interaction process. The system "potentiality", or (real) power to create new structure at the very beginning of interaction process (i.e. before any actual structure emergence) can be universally characterised by a form of complexity called *dynamic information* and generalising usual "potential energy" [1, 3, 5]. During interaction process development, or structure creation, that potential, latent form of complexity is progressively transformed into its explicit, "unfolded" form called *dynamic entropy* (it generalises kinetic, or thermal, energy). Universal *conservation of complexity* means that this important transformation, determining every system dynamics and evolution, happens so that the sum of dynamic information and dynamic entropy, or *total complexity*, remains unchanged (for a given system or process). It is the absolutely universal formulation of the symmetry of complexity that includes the above "horizontal" manifestation and, for example, extended and unified versions of the first and second laws of thermodynamics (i.e. conservation and degradation of energy). It also helps to eliminate a persisting (and inevitable) series of confusion around the notions of information, entropy, complexity, and their relation to real system dynamics in unitary theory (thus, really expressed and processed "information" corresponds rather to a particular case of our generalised dynamic entropy, see [1,5] for further details).

It is not difficult to show [1, 3, 5, 6, 10] that a natural, universal measure of dynamic information is provided by *generalised action* $\mathcal{A}$ known from classical mechanics, but now acquiring a much wider, essentially nonlinear and causally complete meaning applicable at any level of complexity. One obtains then a universal differential expression of complexity conservation law in the form of *generalised Hamilton-Jacobi equation* for action $\mathcal{A} = \mathcal{A}(x, t)$:

$$\frac{\Delta \mathcal{A}}{\Delta t}\Big|_{x=\mathrm{const}} + H\left(x, \frac{\Delta \mathcal{A}}{\Delta x}\Big|_{t=\mathrm{const}}, t\right) = 0 \ , \tag{23}$$

where the *Hamiltonian*, $H = H(x, p, t)$, considered as a function of emerging space coordinate x, momentum $p = (\Delta \mathcal{A}/\Delta x)|_{t=\mathrm{const}}$, and time t, expresses an explicit, entropy-like form of differential complexity, $H = (\Delta S/\Delta t)|_{x=\mathrm{const}}$ (note that discrete, rather than usual continuous, versions of derivatives and increments here reflect the naturally quantized character of unreduced complex dynamics [1,3,5,10]).

Taking into account the dual character of multivalued dynamics, where every structure contains transformation from a localised, "regular" realisation to extended configuration of generalised wavefunction and back (Section 2), we obtain the *universal Schrödinger equation* for the wavefunction (or distribution function) $\Psi(x,t)$ by applying the causal, dynamically derived quantization procedure [1,3,5,10,18] to the generalised Hamilton-Jacobi equation (23):

$$\mathcal{A}_0 \frac{\partial \Psi}{\partial t} = \hat{H}\left(x, \frac{\partial}{\partial x}, t\right) \Psi \ , \tag{24}$$

where $\mathcal{A}_0$ is a characteristic action value by modulus (determined by Planck's constant at quantum complexity levels) and the Hamiltonian operator, $\hat{H}$, is obtained from the Hamiltonian function $H = H(x,p,t)$ with the help of causal quantization (we put here continuous derivatives for simplicity).

Equations (23)–(24) provide a universal differential expression of the symmetry of complexity showing how it directly determines dynamics and evolution of any system or interaction process (they justify also our use of Hamiltonian form in the starting existence equation, Section 2). This universally applicable Hamilton-Schrödinger formalism can be useful for rigorous description of any complex network and its separate elements, provided we look for the *truly complete* (dynamically multivalued) general solution to particular versions of equations (23)–(24) with the help of unreduced EP method (Section 2).

4 ICT complexity transition

We have demonstrated in Sections 2 and 3 the fundamental, analytical basis of complex (multivalued) dynamics of real communication networks and related software systems, which can be further developed in particular applications in combination with other approaches. The main *practical proposition* of emerging intelligent (complex-dynamic) ICT paradigm is to open the way for *free, self-developing structure creation* in communication and software systems with strong interaction (including self-developing internet structure, intelligent search engines, and distributed, user-oriented knowledge bases). Liberated, autonomic system dynamics and structure creation, "loosely" governed by the hierarchy of system interactions as described in this report, will essentially exceed the possibilities of usual, deterministic programming and control.

Practical framework of intelligent ICT paradigm will be based upon permission for various *local* deviations and "mistakes" in system operation in exchange to its *unceasing* search for a *general purpose* realisation, in agreement with the above law of complexity conservation by its transformation (Section 3). The "purpose" represented by software structures of increasing sophistication expresses the "potential" form of complexity, dynamic information, which is transformed into the "accomplished" form of dynamic entropy in the course of chaotic search of ways towards the purpose realisation. One can start therefore with creation of suitable *motivation structures* and system *spaces* (containing a hierarchy of *multiple* possibilities) for their unreduced, *chaotic* interaction with other participating structures.

Complex-dynamical criteria and control parameters of detailed system development are provided by the universal criterion (20) of transition between chaos and regularity and expression (21)–(22) of huge efficiency growth upon transition to the unreduced complex dynamics (they can be specified for each particular case). They imply that emergence of a new, truly complex-dynamic kind of system behaviour will have the form of qualitative, clearly perceived transition in the system operation mode that can be designated as *complexity transition*. As there are many levels of a real interaction process with multiple participants (many frequencies in (20)), one will obtain eventually a whole hierarchy of such transitions, which can be unified into uneven groups of more or less pronounced changes.

Note that the basic criterion (20) can also be applied to the general transition from quasi-unitary (regular) to complex-dynamic (multivalued) kind of ICT structures, where it means that the rigid, low-frequency dynamics of an artificial structure (computer, network) enters in interaction with an effectively high-frequency dynamics of natural intelligence (cf. (21)–(22)) and actually *imposes* its low-efficiency, regular dynamics to the complex-dynamical human component, thus strongly limiting the huge efficiency of the latter. The resulting effective *enslavement* of natural intelligence complexity by a "machine" it has created provides a convincing demonstration of the necessity to realise the ICT complexity transition and profit from the advantages of unreduced intelligence of the *whole* system as they are outlined in the present report.

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