Emergence of observational hierarchies in natural evolution

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Abstract

The starting point for our work are (models for) forest ecosystems. We seek to integrate two sources of knowledge about such ecosystems: the scientific approach from the viewpoint of an exo-observer (one that is detached from the system and has theoretically unlimited observational capacity) and the management approach for utilization (one that has a common history with the managed system and includes the possibility of an endo-observer). Within the scientific approach, these ecosystems are often regarded as being among the most "complex" systems that can be abstracted as objects, whereas their practical management for human utilization (including interferences of an occasionally entangled endo-observer) sometimes has allowed economically reliable predictions over time scales from years up to a century.

Each approach alone seems to be insufficient to solve the theoretical and applied problems of contemporary ecology. Practical experiences on one hand cannot be extrapolated and become invalid under new environmental conditions, whereas ecosystem research on the other hand has not come up with a single example where such experiences could be derived from an theoretical understanding of ecosystems. We conjecture that this failure has theoretical rather than technical origins. Its solution, however, will not only require a broader observational basis including the perspective of endo-observers, also the abstractions from this basis may change. Our metaphor for modeling ecosystems is shifted from energy and matter turnover to a computational problem.

To this end we suppose that information and energy are the primary irreducible entities driving self-organization and structure formation. The history of natural evolution, from the creation of matter until now, may be understood as steady change of phases where the symbolic aspects and phases where the matter aspects dominate. We argue that these phases are related to classification and construction aspects, respectively, and hypothesize that exploration of unknown structures by "agents" always implies this alternation. However, the structures are also partially created by the agents, bringing self-reference into play.

The ("phenotypic") appearance of agents can differ drastically depending on the phase (or the age of the universe) considered. Each agent type is "genotypically" characterized by a certain maximal information processing capacity, eventually leading to an information crisis when no more structures are exploitable. These crises induce a hierarchy of ("genetic") codes, with increasing capabilities for hypothesis building (the agent as endo-observer). These hypotheses are constituted as matter (phenotype construction) and tested; successful hypotheses are characterized by persistence (the agent as interactive constructor). We try to clarify the hierarchy building or emergence of new levels within it by analyzing the relationships among and roles of a number of dualisms: genotype/phenotype, classification/construction, endo/exo point of view, local observer/global context. In a self-referential universe their respective explanatory power depends on the "situation" and on observer perspective. However, it becomes possible to find and test analogies between the corresponding computational crises that must occur in the evolutionary history of such an universe.

1 Introduction

Deterministic models based on mechanistic principles are not able to predict or reconstruct ecological dynamics. The question whether this is a deficiency of our current understanding of prevailing processes at the ecosystem level that will be overcome in the future or rather indicates a principal limitation of process-oriented approaches is still open (Hauhs et al. 1996). We will present arguments in favor of the latter alternative.

Research on terrestrial ecosystems and forested catchments was initiated almost twenty years ago, motivated in part on reports by forest decline symptoms. They led to a devaluation of empirical knowledge accumulated over centuries in forestry, for which scientific understanding was expected to be a substitute. A subtantial amount of financial resources has been spent since; however, the two approaches to the same sort of system do not seem to converge in any sense. On the other hand, the problems which initiated this research are of real practical concern and are mainly unsolved yet. Thus, our overall goal is to integrate different sources of knowledge about forest ecosystems into one consistent view. This should clarify the role science has to play for this kind of systems and ecosystem management decisions.

Science gives no hint why traditional empirical rules for managing tree stands worked in the past and enabled successful timber yield predictions, let alone why they do much less so nowadays. We conjecture that this failure has theoretical rather than technical origins. Its solution, however, seems to require a broader observational basis. We are convinced that the discrepancy between empirical access and scientific investigations for these systems can be traced back to the very different observational situations in which each type of knowledge is gained. The forest manager shares a common history with the system, leading to a sort of non-verbal knowledge about it, which qualifies him as participant of the biological (evolutionary) context, or an *endo-observer*. The scientist approaches the system across its (spatiotemporal as well as functional) boundaries; his instantaneous measurements are ahistorical; he is an *exo-observer*. In addition, the prevailing paradigm for a scientific system description considers ecosystems as (complicated) state-determined dynamical systems, an attitude that is certainly unjustified for evolving biological systems (Stewart 1997).

Our metaphor for modeling ecosystems is shifted from energy and matter turnover to a computational problem, intending to find new *simple* representations for systems and situations which appear rather complex viewed from the "energy and matter paradigm". In this sense the posed problem is of a very general nature and the broadened observational basis may lead to applications completely outside the realm of ecosystem research. We have systems in mind where the observer is also a participator, the classifier is also a constructor. We will try to generalize the concept of an observer far beyond the realm of biological entities. Thus, we want to generalize the different types of knowledge and information to a hierarchy of systems, ranging from "primitive" systems (of the very early universe, i.e. ensembles of elementary particles) to cultural ones, reflecting the historical unfolding of the observable universe through its evolution. However, within a given hierarchical level, we consider only systems and situations which are prototypes for this level, e.g. present extreme cases. For these cases, it has to be tested whether our approach yields a compact description, although the system appears to be structurally rather complex. Guidance is given through a *dualistic* approach, combining and comparing pairs of conjugate terms, such as the above mentioned endo/exo distinction, but also phenotype/genotype, ontic/epistemic, or classification/construction. We will try to elucidate the relative importance of each of these dualisms for different stages of evolution.

2 Basic Assumptions

2.1 Energy and Information

The dominant phenomenon govering the time development of the observable universe is evolution. The idea of a initially highly symmetric, virtually structureless universe evolving to more and more complex structures at vastly different scales lies at the heart of modern cosmology. It is common belief that the control parameter determining the different phases of matter formation is *energy* (or equivalently temperature or also inverse length). The existence of energy gaps implies the possibility of distinct hierarchical levels. Interactions are primarily to be found within such an energy stratum; the laws of nature have an *intralevel* character (Anderson 1991, Farre 1997).

Thus, energy appears as a primary category. A dual category is *information*. We suppose that the relative importance of both categories depends on cosmological time and is growing for information. A hypothetical outside observer endowed with the cosmological time scale would have the impression that almost all "action" takes place at the very beginning of cosmic evolution, followed by a rather dull period. However, the participatory observer evolving together with the system has the impression that most of the action takes place "now". This is partly due to the increasing information processing capacities of observers, demonstrating the role of information as the dominating explanatory category. Of course, the information concept is quite different from that of energy - information presupposes the existence of observers who can process the information. The two concepts refer to different descriptional reference systems. Energy is typically used by exo-observers measuring physical quantities, but having no access to the computational structure and history of the observed system; information is preferably used by endo-observers sharing a context of meaning with the observed system, but having only limited access to external resources or knowledge about them.

Information refers to *differences*, and the perception of differences requires the distinction of inside and outside worlds: observers have internal perspectives. Thus, observers are *local* entities: they have well-defined notions for "here" and "now". Differences are also connected to symmetry-breaking (Ehresmann and Vanbremeersch 1997). Adopting the standard scenario of cosmological evolution as described by high energy physics, the sequence of (spontaneous) symmetry breakings separating the fundamental interactions and freezing out the degrees of freedom responsible for their previous unity (gauge bosons) can provide the building blocks necessary for a hierarchy of observers with increasing computational power.

Our approach is not a mere substitution of the "energetic" (or materialistic) world view by an "informational" (or symbolistic) one. Rather, the two categories are linked in a self-referential way. Both characterize a *relationship* between two parts of the universe of discourse from the inside. One of the parts serves as a basis, possible observers are members of the basis; the other part is the observed or managed or manipulated system. The basis systems are in no way atemporal or spatially homogeneous; they may be divided spatially (inside/outside distinction) or temporally (before/after). Both divisions are of course also symmetry-breaking operations, which, however, do not destroy *global* symmetries and are not spontaneous. Which parts of the basis and which world view lead to a compact (symbolic) representation or efficient utilization depends on details of the actual situation and the system considered.

From now on, we will assume that the universe (of discourse) is finite (less than 10^{180} bits[1]), and every observer is equipped with a phenomenological time-ordered history (past, present, future). The former condition is a minimal requirement for the possibility of an ontic exoperspective, the latter constitutes the basis for an epistemic endoview.

[1] Divide the volume of the observable universe by the Planck volume, and attribute one bit to each Planck cell.

2.2 Classification and Construction

Observation as understood here is generically a passive operation: the (endo-)observer is confronted with a "given" dynamics; his task is spatiotemporal pattern recognition, i.e. *classification*. The observer builds hypotheses about the outside world to identify (spatially) similar or (temporally) repeating structures. The hypotheses are formulated in a symbolic manner, introducing necessarily a coarse-graining to achieve a *finite* description, i.e. they introduce a distinction between the candidate laws of nature and contingent facts (Gould 1995). Within the given resolution, continued observation allows the distinction of valid and invalid hypotheses, leading to denial or refinement of them. The correspondence or (in ideal cases) congruence of symbolic representations and material facts is an *epistemic* category. Succesful classifications require avoidance of self-reference and a finite number of intermediate steps or *termination*. To the extent that the observer and the observed share a common history, there surely exist constraints to the freedom of choice of appropriate symbolic codes. This has the main effect to enlarge the probability of congruences or close correpondences.

The complementary active aspect is *construction*. The more advanced symbolic representations (grammars, languages, rule-based systems etc.) are characterized by an enormous ratio of *potential* configurations and the actually realized ones. The transfer of symbolic representations into material configuration requires a decision among a (huge) number of choices, i.e. leads to a *selection* problem. If the choice is made, a contingent fact emerges, and temporal symmetry is lost (an arrow of time is introduced). For very simple systems, the number of potential and actual configurations coincide: all ("genotypically") possible configurations are ("phenotypically") realized. This is the case for the level of elementary particles (subject to conservation laws) and also for atomic nuclei. Using the energy paradigm, the coincidence is related to the ratio of typical energy gaps and the rest masses of the constituents. More complex systems typically posess a dense band of energetic levels, which combinatorically forbids the occupation of all of them simultaneously. For even complexer ones, the energy picture loses its descriptive relevance.

The two different tasks of classification and construction can both be handled within certain subsets of spacetime. These subsets define the *local Now* of an observer. Outside this region, only classification (past "light cone") xor construction (future "light cone") is possible. To use the computational paradigm, classification alone refers to already executed programs on a Turing machine (TM), construction alone refers to input yet to be given to a TM, and the application of both during the *computational Now* refers to the actual operation of an interaction machine (IM) in the sense of (Wegner 1997). IMs are an extension of TMs in that they are open to an environment from which unpredictable (parallel) inputs are received.

2.3 Information and contextual meaning

The quantification of energy requires the definition of an appropriate zero level. This is far from being a trivial issue (cf. vacuum energy or the cosmological constant problem); however, the quantification of information requires even more. To that end, a reference system or *context* has to be defined. The context consists of elementary units (atoms, terminal symbols) and rule-inferred derived constructs (words etc.). (Examples of such rules are the laws of electromagnetic interaction governing chemical reactions in the case of simple systems.) The basic rules are constituting the *axioms*. Informational contexts are always either incomplete (Turings problem) or self-referential (Gödels theorem) (Barwise and Etchemendy 1987).

Which sort of deficiency has to be chosen depends on the situation: for the classification problem of the observer to be solved in finite time, self-reference has to be excluded, as otherwise finite sets may be transformed into infinite ones by non-terminating recursions. Failure of the Rationalists program ("Wiener Kreis!") demonstrates that complete avoidance of self-reference is elusive and thus such a choice can only be performed as an idealization. For construction tasks, completeness is sacrified (a choice in symbolic space must be made) while self-reference provides powerful construction paradigms (an artificial example where simple construction rules lead to rich structures are iterated maps). Along the evolutionary hierarchy proposed, phases of construction and classification alternate. The transition between them is characterized by computational crises caused by either the Gödelian or the Turing situation, triggering the emergence of new hierarchy levels.

A given hierarchy level constitutes a common context of meaning, i.e. a code shared by the endo-observers of the level. Thus, information content and meaning of messages can be well-defined in an intralevel viewpoint. However, efficient communication requires also synchronicity of "nows" creating a domain in which endo-observers act as network of IMs while their entire context may not behave so externally (Wegner 1997). In the energy paradigm, the intralevel interactions are called *laws of nature* (Farre 1997). However, in this case structural components are considered. In the informational view, a functional perspective is attained; members of a given level share a common history, and the interactions between them require a negligible amount of energy, up to the point that energy as a resource becomes irrelevant. The limiting resources are available storage capacity and transfer rates for information, and most important the power or complexity of the code used. During evolution, the number of possible choices greatly increases, implying that the individual choice becomes more and more improbable (viewed from the outside). Statistically speaking, the (information-theoretic) entropy is lowered: information gathering and utilizing systems are entropy sinks (Caves 1994, Hauhs and Lange 1996).

Usually the concept of information cannot be used across contextual meaning, but presupposes a universally valid code, i.e. implies a preferred reference frame, which is possible only *within* a given level. However, in the situations of computational crises, *interlevel* information transfer will be used to link components of the lower level to newly emerging objects in the higher level. The during this process created new context or code renders (some of) the building blocks of the lower level invisible and inactive. This can be categorically described by the action of forgetfulness functors (Ehresmann and Vanbremeersch 1997).

3 Dualistic approaches

3.1 Classification and Construction

The generic observer in the informational universe is endo in nature: he has evolved as part of the very same universe. Hence, the exo-standpoint necessary for classification has to be constructed via additional constraints or assumptions. One candidate for this abstraction from the joined history and common meaning is the disentanglement by suppressing long-range causal correlations (no EPR situations), i.e. the existence of *local* interactions only. The most basic or "primitive" example for the disentanglement is probably the decoherence and the emergence of classical behavior of a quantum system generated by its classical environment (Zurek 1991).

Of course, the very act of observation has a material aspect also. The sensorial instruments are thought as participating in the dynamics of the observed system, they are members of a lower hierarchical level. Thus, observers constitute a link between the levels of the hierarchy, although the information retrieval and processing takes place only in the higher level (except during computational crises). To solve the classification task in finite time excludes the possibility of infinite recursions. This can in general only be achieved by avoiding self-reference. However, non self-referential axiomatic systems are necessary incomplete (Gödels theorem). As each observer is embedded in the hierarchy of contextual levels, the incompleteness requires decisions or strategies concerning the halting of an observation. Correlated to the relevant spatiotemporal scales of the fluctuating environment, this is achieved by appropriate coarse-graining of the sensors. This renders the observational task operational.

At early stages of the development of a given level, the feedback of the observation on the observed system can safely be neglected. This is the situation where *solvable* (*easy)* classification tasks are fulfilled (hypothesis building is difficult, their validation is simple). Gradually, more and more complex patterns are revealed, with an increasing consumption of resources. At late stages, the most complex tasks are the only left - hypothesis are easily formulated on the basis of already acquired knowledge, their validation is much harder: the feedback becomes substantial, every additional observation removes sensible patterns of the observed system. The final stage is an unavoidable self-observation: a feedback of the observer onto himself. This is the computational crisis of the Gödel type.

This "standardized" scenario for the phases involved in the evolution of a *classificatory* system has a corresponding sequence of events for a *constructive* system, both of which will be integrated to the levels of the proposed hierarchy. To solve the construction task in finite time necessitates a complete axiomatic system. The endoobserver now appears as an endo*constructor*. This enables the existence of infinite recursions. This kind of self-reference is locatable in an unlimited symbolic space of genotypic possibilities. The construction itself is executed by effectors operating on building blocks residing in a lower level. The pool of building blocks is limited. The constructed agents are functionally tested (valuated) by the environment; competition among agents renders the construction task operational.

At early stages the problem of being engaged in non-terminating construction tasks can safely be neglected. This is the situation where easy valuation of construction is performed by the environment (it is difficult to "invent" viable construction schemes, getting an unambiguous decision about their viability is easy). Gradually, more and more complex systems, constituting different solutions to similar problems emerge. From an exoperspective, the performance of these complex tasks requires more and more (external parameter) time (life cycles of constructed systems increase). This has the consequence that the extension of the individual nows diverges. The innovation rate vanishes, the mapping of internal structure to external function ceases to exist. Finally, a halting problem is unavoidable (computational crisis of the Turing type).

We apply the computational paradigm to sketch cosmological evolution as an alteration of the two phases. The lifetime of a hierarchy level is limited by precisely one of each crises. If a functionalist view is used, the level change is located at the "Gödel crisis" (one example for such a level is everything that uses central nervous systems for information processing); if the conventional structural perspective is used, the level change takes place at the "Turing crisis" (biology is everything that consists of living cells). The level descriptions resulting are different in both cases. The two approaches are dual to each other, but in general will not lead both to compact or efficient level descriptions for all situations. In the energy paradigm these level changes are either miraculous (Turing crisis) or invisible (Gödel type).

3.2 Genotype and Phenotype

The classificatory potential of an observer resides in a symbolic space and is formulated in a certain code. Classification is a causal operation (no anticipation required on the part of the observer). The inner representation of completed classification tasks constitutes the *genotype* of the observer. The meaning of the genotype is exclusively accessible from within the same level (from below the code used is too powerful and thus meaningless as information residing within an exo-observer cannot be downloaded across the hierarchy, from above the code is hidden in seemingly stable building blocks). The transition between material facts and symbolic representation is a phenotype to genotype mapping across a hierarchy level (when the respective level boundaries are defined at the Turing type crises).

The construction is a teleological or anticipatory operation. It requires an active selection in the symbolic domain by the endo-observer. The transition from symbolic representations to material objects is a genotype to phenotype mapping (now occuring within a hierarchy level). The construction itself is an execution of statements from the program part of the genotype; the initial situation for the resulting phenotypic object is complemented by a set of data expressing the expectations on the future development of the environment. The genotype/phenotype pair can be described as a prototypical anticipatory system (Rosen 1985). The corresponding valuation of the genotypic choice can only be performed in the open (interactive) phenotypic space to which it is mapped.

3.3 Ordered and Random information

The act of observation implies a *valuation* of information also. The decoding of information is possible only if the observer shares the code in which the information was formulated. In simple cases, there are identifiable emittors and receptors, both of which are relying on a convention delimiting the class of possible messages. In more general cases, parts of the system place information, and other parts of the system gather and utilize this information. The emergence of a shared code in this case is a complex process (Ehresmann and Vanbreemersch 1997), though it may be constrained by physical laws or thermodynamic limits.

The decoding capacity alone is of course not sufficient for interpretation. A well-structured, e.g. deterministic and perfectly predictable sequence of information may appear completely random and structureless to an observer not sharing the context of the source origin. Two well-known examples are iterates of the logistic map in the chaotic regime when the mapping formula is not known, and the pseudorandom number generator which is unmasked as being perfectly deterministic when run twice with the same seed.

These examples demonstrate that the randomness of information depends on the observer's knowledge and is in general a non-calculable quantity. A well-known quantity in this context is the length of the shortest program generating the data as its output, the Kolmogorow complexity of the data. It can be proven that no algorithm can exist to calculate it (Zurek 1989). The proof relies on the Turing halting problem.

Two classes of measures can be differentiated. First-order or structural measures are maximal for completely random data sets and minimal for constant series. Second-order or dynamical measures are small for regular as well as completely random data and achieve their maximum "half-way" between order and chaos (Lange et al. 1997). The quantification of the complexity of information is a typical exo-operation. An endo-observer ("insider") has access to a compact description anyway.

Observers evolving along the alternating phases described in section 3.1. will experience characteristic transitions in the information content encountered at the computational crises. At the Turing type crisis the genotype to phenotype mapping runs into a halting problem, leading to an endless testing of competing phenotypes. The participatory endo-observer (and -constructor) enclosed into such a situation experiences an extended "now" exposed to a seemingly patternless parallel input from an randomized environment (first-order measures approach their maximum values); the genotype code has reached its maximum capacity and though all the action is now, nothing new emerges *within* this system. However, a new exo-observer, hence a new higher level genotype, can emerge from such systems and constitute a solution to the Turing problem. Possible mechanisms which formalize this emergence are the binding of patterns into a colimit in a category theoretical approach (Ehresmann and Vanbremeersch 1997) or the integration of independent competitors into functional units by hypercycle-like catalytic couplings (Schuster 1997). From the exo-viewpoint provided by a new coding facility the very same situation may appear as ordered and simple (first-order measures approach (much) smaller values).

For observers participating in a system near the Turing crisis, the information processing rate reaches arbitrarily high values (within the "old" coding scheme). We propose that the generic time scale of the observers is proportional to this rate. This is an internal or subjective time scale (Hauhs and Lange 1996).
While the internal time scales diverge during the Turing crisis, this old phenotype level now appears as a exploitable resource for the fresh exo-observer. This is the start of a new classification epoch, in which the problem of self-reference can be ignored to begin with. This transition is characteristic of the endo/exo transition separating a constructive epoch from a classificatory one whenever a Turing crisis is overcome.

An entirely different type of transition occurs at the Gödel type crises when self-reference within a finite context becomes the limiting problem for classification tasks. In such a situation, the environment appears complex *before and after* the transition towards a newly emerging phenotype. Here, the situation is "truly" complex, second order measures approach their maximum and the self-referential system encounters correlations over many scales. From an exo-perspective, nothing new can be learned, as every observation has a substantial feedback on the observer and hence loses its status as observation: the exo-observer is transformed to an endo-constructor. The observer has become part of the environment, and selections in symbolic space decide on law-like vs. fact-like aspets of the phenotype. The building blocks assembled by the construction constitute a transition to a new phenotype: a genotype - phenotype mapping is performed.

It is only after this second transition that a new level within the hierarchy becomes complete with its own phenotype and genotype.The different dualisms and situations introduced so far are summarized in Table 1.

	Classification	**Construction**
Conjugate terms	Endo/Exo	Genotype/Phenotype
Initial situation (symbolic domain)	solves a Turing problem	solves a Gödel problem
Initial situation (material domain)	Disentangled parts	universal building blocks
Final situation (symbolic domain)	runs into a Gödel problem	runs into a Turing problem
Final situation (material domain)	resources exhausted	equilibrium achieved
Complexity measures	randomness appropriate	complexity appropriate
Computational prototype	Turing machine	Interaction machine

Table 1: The complementary operations of classification and construction and their respective properties.

4 Ecosystems

Various extreme situations from the evolution of life will be used as paradigmatic examples for which all the abstract notions introduced above can be applied. Living systems combine notions of active observers with properties of classical dynamical systems, hence both the computational and the energetic paradigm apply in part to them. An extension of the proposed scheme into the realm of cultural evolution will be sketched as well as an extension into the prebiotic realm. However, as the latter extension moves away from fully competent observers, a switch from a computational towards an energetic representation becomes appropriate (demonstrating the proposed increase of the importance of information during evolution of the universe).

For solving the classification task of a biological observer exploring patterns from the abiotic environment which constitute the boundary of the associated ecosystem (Hauhs and Lange 1996), we propose two extreme strategies as protoypes. As stated in sec. 2.2, the hypotheses built will depend on the typical spatiotemporal variabilities of the surrounding, as compared to the size of organisms and their reproduction cycle. This does not affect the observation that a multitude or even a continuum of relevant time scales exist simultaneously within (at least) higher organisms (Rosen 1997), convincingly demonstrated by the complex dating mechanisms residing in mammalian brains known as the binding problem (Ruhnau 1994).

One extreme case is observation of spatially rather heterogeneous, but temporally smooth and slowly-changing signals (e.g. weathering of silicates). The corresponding strategy for efficient classification is a high reproduction rate combined with short growth periods (small (micro-)organisms). The importance of such microbial ecosystems is extremely high, as they seem to occur everywhere in the biosphere, more precisely: they are *defining* the extent of the biosphere (Gold 1992).

The other extreme case is a spatially rather homogeneous, temporally strongly varying input (e.g. rainfall on local scales). The corresponding strategy for efficient classification is a rather extended growth period and slow reproduction (trees). Any other organisms are thought as intermediate between these two extremes.

The description and utilization of ecosystems also resembles the energy vs. information paradigm. Science has traditionally focussed on the exoobserver perspective only. There is a further distinction within this view (Mahner and Bunge 1997): the ecosystem of a biogeochemist (functionally defined, e.g. a hydrological unit such as a catchment, concentrating on matter and energy exchange with their environment, treating them as open systems); and that of a biologist (structurally defined, e.g. using biological units such as cells, organisms, populations, etc.). The former leads to an operational definition of its boundaries and a phenomenology describing them as *filters* for their input signals (Lange and Hauhs 1994). The latter leads to an operational defintion of epochs in the history. In this context the question how to decompose or to reconstruct ecosystems is a legal and a highly respected one (though apparently not a very helpful one).

Utilization emphasizes the historic context of descent including emancipation and dependence. Human cultures have increasingly technically emancipated themselves from purely natural ecosystems (and modified them). This leads to an operational definition of reproducible epochs (in dynamic system terminology: initial conditions). The technical ability to impose and reiterate initial conditions transforms contingent natural history into repeatable growth or succession patterns of utilized ecosystems. This reduction uses the self-booting property of biological systems and is equivalent to freezing or simplifying its genotypic information. A typical example is clear-cutting a forest and new planting afterwards. This constitutes a biological reset on the system which is desirable e.g. for yield predictions. In this context the question how to efficiently reproduce a given ecosystem function is an important one (though not a scientifically respected one).

From the epochs of biological evolution, three situations (representating crises) are selected as candidates for a compact description as a computational problem:

1. The emergence of the first living cell (as a new classificator, a new genotype constituting an exo-observer).
2. The emergence of multicellular, eukaryotic organisms (as a new constructor, a new phenotype entrenching higher organisms as endo-observers).
3. The situation of mature forest ecosystems with a stationary external budget w.r.t. matter and energy fluxes (as a constructor approaching its maximum coding capacity) encountering a Turing type problem for the involved endo-observer from this hierarchy level.

4.1 The emergence of the first living cell

It is an astonishing fact that life emerged only once and very soon after the surface temperature of the young earth allowed the condensation of an ocean (Condie 1997). Potential locations where this might have happened are places protected against cosmic impacts and high energy radiation close to strong thermodynamic gradients such as Archaean equivalents to black smokers (Bock and Goode 1996).

Microorganisms learned about and adapted to the various resources on the primordial earth. However, after its "quick" initiation, for more than half of evolution history, life remained unicellular, discovered, developed and perfected all essential microbial metabolism types (Conrad 1986). Hence these primordial organisms were universal learners of the "weathering type" mentioned above. Concurrent with this microbial epoch much of the geochemical changes unique for the earth took place: The development of a felsic (continental) crust and the development of an oxidating atmosphere (Condie 1997). At least in the latter change life played an active role.

Form a computational perspective early microorganisms can be regarded as paradigmatic classifiers that could ignore the (global) feedback cycles started (caused) by them. Due to their unique coding capacity they attained an exo-observer status w.r.t their abiotic resources, which they could treat as effectively independent (leading to an evolution of the various microbial "specialists"). We regard these primitive microorganisms as Turing machines (Tab. 1), for which their specific environment forms a fixed, predictable input.

The purely microbial epoch ended when their waste product (atmospheric oxygen) became a major environmental factor for the further evolution of life at around -2 Ga. In the proposed scheme this set the stage for the second transition.

4.2 The emergence of multicellular life

The next evolutionary breakthrough was the emergence of eukaryotic cells which subsequently served as universal building blocks for all higher forms of life (structurally complex, but functionally relatively simple)(Wolpert 1995). They require free oxygen of more than 1% and occurred soon (perhaps as soon as possible) after this level was reached in the atmosphere.

From a computational perspective the feedback loop through the atmosphere can be regarded as a self-referential system. Life encountered on construction as soon as further classification (from a microbial perspective) became impossible. This transition towards higher forms of life with complicated phenotypes can be viewed as a solution of the Gödel crisis discussed above. From this time onwards properties such as sex or death become implicated into developmental biology. In a computational perspective the ontogenesis can be regarded as an instance of an IM.

4.3 The crisis limiting life

From an external purely functional perspective energy and matter cycles of forest ecosystems (usually regarded as the most complex form of life in terrestrial environments) can be simplified to trees and microbial strategies (as the ultimate primary and secondary producers maintaining the matter turnover, though not necessarily closed). Unlike in Archaean ecosystems the thermodynamic gradients exploited by decomposers within a forest ecosystem have themselves a biological origin (e.g. supplied by photosynthesis). In extreme cases (e.g. highly-weathered tropical soils) the whole ecosystem including a myriad of internal food chains may depend on just one metabolic pathway (photosynthesis). The trees that are responsible for the primary production in such cases follow the typical strategy of the "rainfall" type (cf. above). In regions whitout any long-term changes in climate nothing "new" can be learned about rainfall: a huge number of different species compete over long phenotypic life-spans for subtle advantages in fitness.

Here we regard this as a scenario for a halting problem experienced when a code reaches its capacity limits. In terms of abiotic resource exploitation at the ecosystem level a further improvement is not conceivable (even with human inventiveness included, quite the opposite: it is in fact extremely difficult to replace tropical forests on deeply weathered soils by any managed ecosystem). That is why these systems can be regarded to have achieved an equilibrium with respect to their learning task.

4.4 Ecosystem utilization revisited

The virtual contradiction between a functionally mature system behaving rather predictable for an exo-observer and the internal complications involved in the construction of such a system reappears in many contexts of human technology. The dilemma of contemporary ecology mentioned in the introduction is just one example. Many histories of recent "high-tech" provide more: Information engineering (software and hardware) has achieved an impressive and wide gap between the sophisticated construction tasks involved and the simple user-friendly applications forming a new communicational context (e.g. the internet). The number of people capable of switching between the role of a (de-novo) constructor and an experienced user of such technologies declines rapidly. In ecology, however, the traditional paradigm implies that the understanding of a forest ecosystem in its abstraction as a dynamic system will ultimately help practitioners to predict and control it. Yet convincing examples for the validity of the statement are still lacking.

In the compuational perspective proposed here, forestry is an empirical tradition that searches for an optimal use of a system's aspect (total stem biomass production) that is irrelevant to information processing within the respective system itself (such as total heat dissipation in a computer: It is true, fundamental, but irrelevant in most applications). Ecology as a science is like a technician seeking to sketch the wiring plan and locally quantifying energy dissipation inside a computer on which a software problem has occurred.

5 The enfolding of a hierarchy?

This approach has to be tested by transfer to other candidate levels along the proposed hierarchy. If it proves as a useful supplement to the dominating energy paradigm it should automatically yield a compact description of those issues that have been notoriously difficult to address using the energy and matter abstraction.

5.1 The cultural level

With this terminology we continue the conventional structural perspective (culture is everything that involves humans). The emergence of human culture is intimately linked to the capacity of human speech (Diamond 1995). The technical achievements allowing an increasing emancipation from or control over ecosystems required the concurrent development of a new code (Deacon 1997), hence the installation of a new exo-observer.

Today, the technological knowledge and capabilities w.r.t exploitable resources creates a global feedback and hence a self-referential system, in which the preceding strategies of classification and control run into a crisis, mainly due to their own success (Horgan 1996). That is why our present environmental situation can be regarded as a higher-level recapitulation of a scenario from which multicellular phenotypes emerged: a computational crisis of the Gödel type.

In contrast to the distinction of a biological and cultural level based on structural aspects,crises of "Gödelian" type lead to a complementary classification focussing at information processing. In this case it would be the central nervous system of multicellular organisms that integrates a level, which currently approaches its capacity limit. It may be no coincidence that we are just experiencing the potential of a new coordination system in the form of the internet (Johnson et al. 1998) that may once serve as a seed for a new "phenotypic" level to emerge.

5.2 Lower levels

During prebiotic evolution there may have been two more situations which allow to use the metaphor of an observer/constructor in a crude form. One already mentioned is the first appearance of a combinatorial (genotypic) space transcending the size of the universe with the first macromolecules. In the proposed terminology this event corresponds to another Gödelian crisis. Their combinatorial abilities formed the highest level of information processing until the advent of central nervous systems. Macromolecules are the first candidates for classical objects, and thus for an intricate local feedback between quantum and classical level.

Macromolecules can thus be regarded as a new phenotypic level. Their "final crisis" is again of a Turing type when their mutual catalytic reactions engage in an endless random network reaction, as sketched by the concept of NK networks (Kauffman 1993). The solution of this crisis forms the first living cell (emerging as an attractor in such a network).

One more level allows the notion of observation in the context of decohering quantum systems (Zurek 1991). In that case the whole environment serves as the classical context. In our scheme this situation that lead to the first atoms is linked to a Turing type problem (the corresponding new structural level uses atoms as basic units, i.e. chemistry).

We will not stretch this speculation any further. As the presented examples demonstrate, a balanced (alternate) use of ontic and epistemic criteria allows to give a compact and integrative account of a world that may not only appear as complex but also *be* so right now for humans. The selfreferential character of this approach implies that it cannot be put to ordinary experimental test (trying to perpetuate an exoperspective of which we hypothesized that it comes close to its principal limits). However, the proposed perspective may serve as a seed focussing the attempts to reorganize the knowledge and competence in dealing with the relation between culture and nature.

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