The Genealogy of Biomimetics: Half a Century's Quest for Dynamic IT

Mikkel Holm Sørensen

Dept. Digital Aesthetics and Communication,
IT University of Copenhagen,
Glentevej 67, Copenhagen 2400 NV, Denmark
megel@itu.dk

Abstract. Biologically inspired approaches to the design of general IT are presently flourishing. Investigating the scientific and historical roots of the tendency will serve to prepare properly for future biomimetic work. This paper explores the genealogy of the contemporary biological influence on science, design and culture in general to determine the merits of the tendency and lessons to learn. It is argued that biomimetics rests on bona fide scientific and technical reasons for the pursuit of dynamic IT, but also on other more external factors, and that biomimetics should differentiate the relevant from the superficial. Furthermore the search for dynamic capacities of IT that mimicking adaptive processes can bring about is put forward as both the history and raison d'être of biomimetics.

1 Lifelike – á la Mode

Biology is enjoying enormous attention from different scientific fields as well as culture in general these days. Examples are legion: The victorious naturalization project in philosophy and psychology spearheaded by cognitive science in the second half of the 20th century; the exploration of biological structures in the engineering of materials or architectures [1]; a dominant trend of organismoid designs with 'grown' curves replacing straight lines to convey a slickness and efficiency not previously associated with life;[1] World Expo 2005 being promoted under the slogans "Nature's Wisdom" and "Art of Life";[2] and biology's new status as the successor of physics as the celebrity science which gets major funding and most headlines.

These examples are neither historically unique nor culturally revolutionary. Life and nature have been fetishized before. Yet the fascination with the living has never previously dominated with such universality and impetus, as we presently experience. So we might ask: What is the reason for this ubiquitous interest in life and is it a result of cultural and scientific progress or merely an arbitrary fluctuation soon to be forgotten again?

In order to prepare properly for future biologically inspired approaches to IT design, this paper investigates the roots of the biological dominance by reconstructing the

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[1] Think of cars, sports apparel, furniture, mobile phones, watches, sunglasses etc.

[2] http://www.expo2005.or.jp/

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recent history of techno-scientific ideas. A history that can be characterized as a pursuit of dynamic IT. The objective is to distill important lessons learned to provide good conditions for the continued effort to develop dynamic IT through biomimetic design by identifying the proper challenges to embark on and dead ends to avoid.

2 Biomimetics: Definition, Characteristics, and Motivations

The first step in this investigation of biologically inspired approaches to IT design[3] is clarifying and qualifying the notion of biomimetics [2, 3]. 'Biomimetics' has been chosen as the best unifying notion for biologically inspired approaches to design of dynamic artifacts being intuitively descriptive and adequately precise. If the following analysis reveals a specific or even idiosyncratic notion of biomimetic design, it hopefully nonetheless contributes to an increased awareness of the conceptual foundation for biologically inspired approaches in general and helps prevent misunderstandings and conceptual vacuity.

According to Miriam Websters online dictionary biomimetics is:

the study of the formation, structure, or function of biologically produced substances and materials (as enzymes or silk) and biological mechanisms and processes (as protein synthesis or photosynthesis) especially for the purpose of synthesizing similar products by artificial mechanisms which mimic natural ones.[4]

This definition covers two slightly different meanings of biomimetics:

1. The artificial synthesis of naturally occurring materials, substances or other structural configurations.
2. Mimicking biological processes in creating life-like products.

Both meanings concern the synthesis of specific materials or structures, i.e. the synthesis of a certain 'end product', and they merely differ in how directly and in which manner the product is brought about. Biomimetics thus characterized is not an appropriate label for an IT design methodology. Instead I would like to put forward a definition of biomimetics more suitable for the approach:

3. The mimicking of complex self-organizing natural processes to obtain dynamic artifacts harboring adaptive and self-maintaining capacities.

Whereas 1) and 2) concern the creation of *fait accompli* products, a biomimetic IT design methodology 3) instead creates dynamic 'produces', i.e. evolutionary processes involving IT devices that adapt in use [4].

This does not mean that biomimetics is 'anti-materialistic'. On the contrary, a better integration of software and hardware will become an important objective for biomimetics. Firstly in an effort to enhance physical objects and spaces with digital dimen-

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[3] Design is a broader notion than engineering and covers all aspects of creating artifacts (methodological, aesthetic, sociological etc.) whereas engineering only concerns the concrete bringing forth of the artifact.

[4] http://www.m-w.com/cgi-bin/dictionary

sions, providing novel functions free of spatial constraints [5]; secondly to develop self-assembling, evolvable and re-configurable materials for a ‘deeply’ and ‘integrated’ dynamic IT adaptive at both software and hardware level; thirdly in the study of computation itself, with models integrating structural and topological characteristics of natural computation as it occurs at the chemical level (e.g. ’lock and key’). In addition integrative design becomes a necessity as increasingly miniaturized hardware starts having idiosyncratic characteristics due to microphysical effects. Such miniscule hardware will have to be functionally coupled with software in some way and collective ‘growth’ seems a good remedy for heterogeneous characteristics.

2.1 Biomimetics: Design for Dynamics

A biomimetic design methodology capitalizing on the self-organizing capacities of evolutionary processes might appear to be a contradiction in terms. ‘Design’ normally characterizes an intentional and teleological strictly human practice whereas natural order arises ‘blindly’ and *post hoc* from variation, selection and retention cycles. Biomimetic design thus either means ‘un-designed design’ or erroneously project intentionality into adaptation.

According to [6] a crisp distinction between the teleology of design and the causality of evolution does not stand up to close inspection. The argument goes, correctly (cf. [7, 8]), that because the human brain itself basically operates by amplification of fluctuations (variation, selection and retention dynamics) thoughts and ideas are evolutionary selected *post hoc* rather than deliberately created *de novo*. The difference between cognition and other evolutionary dynamics therefore becomes merely ontologically regional and not intrinsic. If our designing skills in other words are just the result of high level evolutionary processes there is no essential difference.

The middle way, which I will put forward, is that there is a significant difference between human design and other evolutionary processes, if only in degree and not in kind, but that this on the other hand does not render the idea of biomimetics incoherent. Despite some terminological fuzziness and the merit of the argument of [6] with respect to cognition, the notion of biomimetics nonetheless adequately covers the specific design methodology under scrutiny here. Whatever the micro-processes underlying cognition, there is a difference between the emergent macro-process of human deliberation and the agent-less achieving solutions merely by due means (e.g. by an autonomously self-organizing technology). In fact a biomimetic methodology is quite different from conventional design approaches, and the outcome no less different. The notion of design simply changes when the role of agency in designing is distributed and even hard to identify, as is the case for example with evolutionary algorithms. The standard notion of design as top-down controlled act no longer holds if parts of the design emerge from self-organizing processes [4]. Moreover identifying the ‘agency’ responsible for a specific state of affairs is pivotal for psychological and ethical issues related to technology and this becomes relevant with increasingly autonomous technology.

The concept of biomimetics also needs qualification in a different sense. The principle of nature primarily mimicked by a biomimetic approach to IT design - adaptive dynamics - is not exclusively biological. Much research suggests that the self-organization of groups by variation, selection and retention is a universal ordering principle governing basic physical laws as for example crystal growth to sociological processes such as the proliferation of ideas [7, 8, 9, 10]. Biology is just one, albeit very prominent, domain of evolutionary dynamics and happened to be the field first described by such terms. Again this lack of terminological adequacy is not harmful if the notion is deployed rigorously for the specific approach characterized in this paper.

On the basis of this terminological clarification, biomimetics can be characterized. Biomimetics is a design methodology for complex artifacts, deployed to support human design with self-organizing evolutionary mechanisms. Biomimetics is a 'meta-governing' approach in the sense that it retains human control of the overall functional norms of artifacts while exploiting evolutionary processes to provide the functions required (cf. [11]). Biomimetics provides simultaneously improvement of our design and in specific circumstances reduction of the labor going into it by leaving some parts of design to evolutionary self-organization. Biomimetics thus seeks to capitalize on the respective (and complementary?) strengths of evolutionary processes and human creative and teleological capabilities [29].

There is a range of reasons why a general bio-inspired tendency has arisen and most probably will continue to grow within IT-research. Let us take a look at some of these to get a better picture of the nature of biomimetic IT design.[5]

One of the main challenges facing IT design is finding the means to develop and maintain ever growing IT systems. IBM's Autonomic Computing Project[6] is motivated by estimations that the development and maintenance of future IT systems will be impossible without new ways of designing such systems. IT needs to take care of itself, and living systems provide so far the only examples of just this capacity. Life has developed means to evolve, develop and learn by adaptive dynamics and since we have got sciences concerned with the organization of adaptive systems - primarily biology but also younger transdisciplinary fields such as dynamic and complex systems theory - it is instructive to consult models and theories from these fields when developing future IT.

Second, our cognitive capabilities are evolutionarily constrained and we simply cannot fully overview, let alone control, very complex structures or processes. History is filled with examples of how technologies turned out differently than expected and dispatching itself form our control, and we have no reason to believe that this is about to change.[7] Who could predict that the surfing behavior resulting form the introduction of the remote control would change the very content of TV broadcasting [5]; that SMS-organized mobs would bring about social change because of a simple feature on mobile phones [12]. Faced with highly non-linearly dynamic and complex systems our cognitive capacities are simply inadequate and leave us without a chance when trying to analyze the long term and global consequences increasingly important with growing systems. Add to this fluctuating user practices increasing proportionally to the freedom technology provides. Acknowledging our limited powers we should

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[5] For supporting or additional reasons to apply biomimetics see [1, 2, 3, 4, 9, 11, 13]

[6] http://www.research.ibm.com/autonomic/

[7] The uncontrollable nature of technology is the very basis for the argument of 'technology determinism' popular among luddites and variants of philosophies of technology.

abandon the notion of a fully controlled top down design process and join a fruitful alliance with some of nature's benevolent ordering principles.

Third, modern theories of complex adaptive systems have gained valuable knowledge on dynamic processes and offer models for the local behavior of constituents as well as global characteristics of systems. This conceptual toolbox will prove immensely important in designing IT systems as nested and hierarchical complexes of systems interacting on multiple levels. Further, the theories facilitate scaling to avoid disintegrated 'stratified' views.[8] The quality of future technology depends on a better general understanding of interacting systems on different scales, from device-device to whole networking societies. IT has to be designed in ways that accommodate rapidly changing practices, mobile, long-distance and trans-media corporations and other forms of (unforeseeable) changes of conditions. From the design of individual devices to the general organization of IT systems architectures and protocols must be mutually supportive to carry biomimetics to its full strengths [2, 3].

3 Genealogy of 20th Century Bio-centrism

The present interest in life is not historically unique, but seems to occur periodically. In relation to biologically inspired design of IT, technology has always been modeled *after* as well as been model *for* the dominant conception of life. This dialectics stem from our desire to understand and master nature. To (re-) produce is to comprehend – *verum et factum convertuntur* – has been the credo through scientific history. Hence by recreating life we might hope to get behind the veil of nature's mystery and peek into God's workshop. The only variations in this perennial dream have been changing époques metaphysical conceptions of life. For example the ancient sculptures created in dirt thought to be one of the four basic elements, Hellenic hydraulic automata modeling Aristotelian 'motivation' and 'movement' ('movere' is the etymological root of both motion, emotions and motivation), the intricate mechanical animals and chess players with the dawning mechanistic natural science, steam driven machines of the 19th century thermodynamics, the postwar computational robots and self-organizing ALife at the turn of the millennium.

The bio-techno pivot is completed by the fact that the technological reproduction of nature is fueled by mans perpetual religious and pragmatic awe for the ingenuity of nature's 'design'. This awe is so firm that it has been difficult to convince people (many are still not convinced!) that the 'design' of nature in fact emerges spontaneously by self-organizing processes without any teleological agency.

However scientific developments since the late 19th century paved the way for a hitherto unparalleled blossoming of our fascination with the living and not least the efforts to make good use of our insight into its governing principles. During the last century science became increasingly preoccupied with systems, complexity, dynamics and information. Phenomena that are all notoriously manifest in organisms and thus biology naturally took the center of the scientific stage. At the same time pollution entered the stage and sympathy for nature rose. After a following period of dichoto-

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[8] As instrumental as the 'software - hardware' distinction is descriptively, it might turn out to be a methodological hindrance for future IT design if taken ontologically.

mization of nature and technology, scientific insights into the wonders of complex systems proliferated. From being pictured as slow, vulgar, dirty and beastly nature suddenly became appreciated for speed, immunity, efficiency and economy. Capacities normally identified with hi-tech but now borrowed from nature.

In the following sections I will provide a brief reconstructions of the main scientific and technological tendencies of the 20th century that led to the present interest for living systems. The reconstruction is divided into historical themes, which should not be taken rigidly. Historical overviews are by nature selective and begin *in media res*. Besides I have no wish to undertake a comprehensive review of recent scientific history. To simplify and clarify matters cybernetics will be our protagonist; both as our point of departure and as the undercurrent of the genealogy of biomimetics.

3.1 Cybernetics

Like all other cultural manifestations, cybernetics did not arise in a vacuum but grew from scientific development embedded in a historical context [14]. Important scientific discoveries and accumulated knowledge fertilized the ground for the converging ideas for research in missile-guiding systems, animal behavior, sociology, neurology and computation around WWII. Cybernetics was founded by a more or less coherent movement of various leading scientists and engineers who met from 1946 to 1953 at the so-called Macy conferences (after the Josiah Macy Jr. foundation, which funded the meetings). Moved by discoveries made during the previous decades within mathematics, physics, biology and chemistry the participants set out to explore processes in complex systems. In fact the very idioms 'complexity' and 'system', together with 'feedback', 'circular causality' and 'information', were created by the cyberneticians in their pursuit of fundamental models for dynamic systems. One of the primary motivations – at least among central figures such as Norbert Wiener, Arturo Rosenblueth and Warren McCulloch – was the similarity between certain mechanical and biological processes. In particular, animal purpose guided behavior, or 'teleology of organisms' as they put it themselves, became the model for self-adjusting machines. Purposeful behavior seemed basically to consist in adjusting behavior by recursively computing the difference between present state and the reference state. This simple feedback-cum-computation model of an almost supernatural phenomenon as teleology promised further solutions of hard philosophical riddles of the mind.

For early cybernetics the computation taken to be the substrate of teleology was, unlike its successors classical AI (GOFAI) and cognitive science, conceived of as strictly mechanical [15]. The important difference is that the computational paradigm for intelligence and semantics represented by GOFAI and cognitive science took computation to consist of rule-guided manipulation of symbolic entities already endowed with meaning or gaining meaning by the syntactical operations themselves. Cybernetics did not operate with such 'semantic computation'. Intentionality and semantics was instead taken to be, at best, higher-level phenomena *arising* from computational processes. In contrast GOFAI and cognitivism seemed to sneak in semantics through the backdoor via syntactical slight of hand by projecting higher-level characteristics into semantic, intentional or normative building blocks with the genesis indefinitely far back in evolutionary history. The cybernetic idea, which is being echoed today in modern cognitive science, is that if seemingly irreducible phenomena relating to the mind cannot be explained (either as real phenomena or 'folk psychology') as the result of processes deprived of such qualities, the same phenomena cannot logically be explained by evolution. Then they must somehow be put into each organism (by God or miracle). A static understanding of mental capacities dictates that either they have always existed beside the physical system (a scientifically unsatisfying dualism) or they are just illusions (phenomenologically inadequate). So like in Hegelian dialectics cybernetics gives the modality of such elusive phenomena the position between pure being and non-being namely becoming. Intelligence is explained as a process capacity [16, 17, 18].

Worth noting is the cybernetic intuition of what we today call emergence of global systematic capacities (e.g. purpose guided behavior, adaptivity and self-maintenance). Through a full-blooded and honest adherence to a mechanical conception of algorithms early cybernetics acknowledged the need for a dynamic conception of the mind.[9] Properties arising from complexity such as non-linear dynamics and self-organization formed the core of this emergentist explanation of purposeful behavior arising from mechanical processes. Mechanical in the sense of formally describable processes giving rise to self-regulating behavior without any entelechy or teleology in the standard sense. Cybernetics thus placed itself between the reductionism of traditional physicalism and the transcendentalism of (some) philosophical approaches, by stressing the scientific importance of mathematical models while making room for the autonomy of emergent levels of description. This turn represented an early version of a slowly propagating undercurrent of science towards interest in processes and dynamics instead of traditional predominantly atomistic and structural scientific models. In more grandiose terms cybernetics manifested a general movement from "substance metaphysics" to "process metaphysics" of 20th century science [16].

Over the years cybernetics began stressing the contribution of the system itself in processing input to behavior. This 'second wave' of cybernetics reached its zenith with [19], which argued for the 'constructivism' of systems orchestrating their inner organization in response to interactions with their environment. Whereas early cybernetics sometimes resembled behaviorism, its dominant precursor, by the early 1970s it had reached the opposite pole with theories of self-organization and 'autopoiesis' of Humberto Maturana and Francisco Varela. These theories opened up the 'black box' of cognition to an extent that seemed to occlude everything external. From being a general philosophy of complex systems cybernetics had come to stress epistemology. Yet, in the true spirit of cybernetics such self-organizational epistemological characteristics was still viewed as integrated aspects of the overall self-maintenance of adaptive systems [20].

3.2 The Ratio Club

On the other side of the Atlantic, early cybernetics had a stepsister, heavily interweaved with the Americans, but prominent enough to deserve separate treatment here.

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[9] It must be noted that the cyberneticians did not form a homogenous group advancing a single coherent theory. For differences in conceptions of 'mechanics' see [15].

In London a group including Alan Turing, W. Grey Walter and Ross Ashby, named The Ratio Club, met to discuss scientific and engineering questions also partly motivated by work on war machinery. In their interaction with the American cybernetics, The Ratio Club members came to play an important role as founders of the second wave cybernetic and the increased focus on self-organization.

Although Ross Ashby only participated in a single Macy meeting (the 9th) he was very influential on cybernetics. At his only appearance Ashby presented his ideas on the 'homeostat'. The homeostat is an (abstract) adaptive automata, which keeps essential parameters at equilibrium by interaction with its surroundings while letting other parameters fluctuate when required. The homeostat provided a formalization of the self-maintaining principles of complex adaptive systems, as manifested by life; the dynamic balancing between 'freezing' into total order and disintegrating into pure chaos. The homeostat depicted complex adaptive systems as inherently "poised at the edge of chaos" as it was later phrased by one of Ashby's famous pupils Stuart Kaufmann. Ashby was thus responsible for placing complexity and self-organization at the heart of *principia cybernetica* and its subsequent metamorphism into its second wave.

The neurologist and engineering genius Grey Walters is an excellent example of the spirit of the time and the renaissance-like feats it fostered. Walter conducted pioneering research in neurology (including inventing the EEG) and his work on defense systems resulted in the radar-display still common in marine and aviation control today. But his explicitly biomimetic work on the two autonomous robot 'tortoises', Elmer and Elsie stands out as the most visionary. On a purely mechanical architecture the tortoises were designed with bio-analogue feedback guided 'needs', which gave rise to seemingly 'motivated' and spontaneous behavior. Endowed with simple photo and tactile sensors they had photo-tactic capabilities enabling them to locate their lightened hut when 'hungry', i.e. for their batteries to be recharged and to leave it again when batteries where charged and the light, due to a switching mechanism, became aversive. Walter's work remains an astounding study in ingenious robotics and a milestone for biomimetic history as an early example of the prospects for implementing even idealized biological principles. It is worth quoting Walter J. Freeman's praise of Walter's work at length:

> *The significance of Walter's achievements can be understood by recognizing that these complex adaptive behaviors came not from a large number of parts, but from a small number ingeniously interconnected. These devices were autodidacts. They learned by trial and error from their own actions and mistakes. They remembered without internal images and representations. They judged without numbers, and recognized objects without templates. They were the first free-ranging, autonomous robots capable of exploring their limited worlds. They are still the best of breed...[]... His devices were the forerunners of currently emerging machines that are governed by nonlinear dynamics, and that rely on controlled instability, noise, and chaos to achieve continually updated adaptation to ever-changing and unpredictable worlds. He can well be said to have been the Godfather of truly intelligent machines* [21].

3.3 Evolutionary Computing

If cybernetics soon became neglected by its offspring, computer science, GOFAI and cognitive science, its current resurrection was nevertheless prepared by developments within the family itself. In 1960s and 1970s the computer scientist John Holland developed Genetic Algorithms (GA) as a general way of creating software solutions by evolutionary adaptive processes. Sidestepping questions of intentionality, the mind and other philosophical issues, Holland showed how algorithms mimicking evolutionary processes were very potent in searching, problem solving and coping with uncertainty and change. In contrast to other post-cybernetic biologically inspired approaches to computational engineering, Holland was not interested in optimization or solutions to specific engineering problems *per se*. He wanted to model adaptation formally leading to a general understanding [22]. The GA model Holland presented in [23] was algorithms organized in population of competing chromosomes coding for different solutions to a given problem. Chromosomes coding for successful solutions where reproduced by the exchange of genetic material (via crossover) and random mutation. Due to the speed of computers evolution of solutions over many generations allowed for fast and reliable almost automated software programming.

What Holland's work made clear was that faced with unknown tasks, changing conditions or other uncertainties, populations of candidates undergoing heritable variance and a good selection heuristics is a potent strategy. Holland's work demonstrated how nature's principles for problem solving were - at least in some domains - reproducible and generally applicable. When exposed to the prisoners dilemma, the traveling salesman or other non-trivial computational tests, GA's proved to be reliable and remarkably fast in finding solid solutions and 'rational' strategies. The results were very convincing and seemed to provide a powerful tool for dynamic automated problem solution. So although of great theoretical strength, it was the pragmatic value of GA's that paved the way to the prominent status that evolutionary techniques enjoy today. Engineering focused computer scientists, normally not interested in other fields, suddenly realized the value of theoretical cross-fertilization. GA's bestowed genuine adaptive dynamics upon standard architectures and self-organizing technology took a significant step forward.

3.4 Neural Networks

Parallel and more architecturally focused developments within computer science were to place cybernetics on the agenda more directly. The rise of neural network theory, or connectionism as it was soon named, in the 1980s was a reemergence of cybernetic ideas. In their seminal paper from 1943 McCulloch and Walter Pitts described the brain as a network of simple neuronal units each firing according to the net-sum of inhibitory and excitatory inputs and the firing potential of the neuron [24]. Many heavily interconnected neurons facilitate interesting higher-level computation by simply firing or not due to the non-linearity of their collective behavior. Such digital dynamics resembled bivalent logic, thought to be the essence of reasoning, and the analogy to human thinking was clear. Their ideas soon gave birth to a new architecture for computation called artificial neuronal networks. However, for various technical and historic reasons, the von Neumann architecture remained dominant.

In the early eighties the connectionist approach took a leap forward aided by improved hardware and increased scientific attention. The results were promising enough to attract attention from mainstream computer science and AI. The primary attraction of neural networks laid in their capacity to model learning and adaptation, which GOFAI was not able to provide. In addition, with the renewed interest in biology the model gained favor by its greater biological correspondence. So although neural networks were highly idealized and only partly flexible, as they must be trained anew for every new task, they still had a biological flavor long missing.

Neural nets remain burdened by architectural hurdles today as such networks take vast amounts of interconnections to be of practical interest. So far neural networks are mostly simulated on conventional platforms. Yet, the jury is still out as to whether neural nets hold the key to future dynamic IT. Given the overall qualities of neural nets demonstrated thus far, it is worth developing methods for creating large-scale neural nets with complex architectures. This has the potential of providing a serious alternative to conventional computers. Again software-hardware integration seems to take center stage, because neural net architectures may provide the means to revolutionize this aspect of computing.

3.5 New AI and Evolutionary Robotics

In response to very poor result within GOFAI, especially if compared with the self-confidence displayed at the outset, roboticists started suggesting new ways of conceiving intelligence in the late 1980s [25]. In the place of symbolic computation, low-level motor capacities were put forward as the basis of cognition. AI and robotics became heavily biologically inspired and turned their interest from human level reasoning and language to simple animals and their embodied negotiation of the environment. Intelligence was no longer taken as an isolated capacity by a discrete system but a descriptive term for the interactions between an autonomous system and its environment. Biological notions such as 'development, emergence and functional coupling became in favor in New AI and robotics. Thus roboticists started implementing ideas from evolutionary computing to develop control mechanisms, and even morphology and physiology, for both virtual and physical agents. From being marginal ideas, notions of decentralization, bottom up organization and not least embodiment by the mid nineties had become dominant concepts in robotics, New AI and cognitive science and buzzwords within most other academic disciplines involving cognition.

3.6 Artificial Life

Simultaneously with the (re-) emergent focus on embodiment and interactive processes in New AI, cognitive science and robotics another adjacent field was forming. Building on the theoretical foundations of molecular biology and computer science researchers started studying (some hoped to create) life *in silico* or Artificial Life

(ALife) as Chistopher Langton baptized the field in 1987 [26]. The marriage of molecular biology and computer science was straight forward due to an underlying functionalism *a la* GOFAI, regarding life as consisting in computational processes on information stored in digital DNA. Thus whether the substrate of the life investigated was carbon or silicon was a somewhat irrelevant empirical matter, at least for so called ‘strong ALife’. By not arbitrarily confining focus to the carbon-based systems we happen to know, ALife could contribute substantially to a general study of life - “life as it could be” [26].

Even if the metaphysics of this self-claimed pioneer field represents the zenith of a reductionistic computationalism (as represented in physics by Steven Wolfram’s radical algorithmic theory of the universe), a lot of valuable work relating to evolutionary capacities of software has been done. With its refusal to limit the scope to things we are familiar with, ALife provides inspiration for biomimetics also sometimes on the verge of science fiction.

3.7 Swarm Intelligence

In close relation to the work within New AI, robotics and ALife, emergentist models grew from ethology and biology as well. By studying the heavily collaborative processes of social insects such as bees, wasps, ants, and termites, valuable knowledge about the rise of productive global functions of swarms of individuals was gained. Similarly to neuronal networks, swarms of insects carrying out relatively simple tasks proved capable of rather complex feats. By exploiting strikingly simple organizational methods, social insects were shown to behave as a unified intelligent super-organism. For example ants capable of foraging with mathematically optimal distribution and finding shortest paths to food sources or termites practicing advanced agriculture and building architecturally impressive nests [13].

Social insects widely use indirect communication in their grand collective labor. Stigmergy (from the Greek ‘stigma’ = sting and ‘ergon’ = work) is a good example of indirect communication by (re-) configurating of the environment, which evokes a specific subsequent behavior in an animal. Stigmergy refers to a triggering effect when e.g. a hole in a wall evokes an ant to put in the missing pellet of dirt. In this way the organization of building is distributed structurally into the environment and arises self-organizationally *ad hoc*.

An example of stigmergy is the chemical organization by pheromone trails. By leaving trails of evaporating pheromones ants have a dynamic communication system allowing for efficient organization. The principle is very simple, just as reliable and consists in pure ‘mechanics’. The trail used by the ant first returning from foraging is likely to have the most powerful scent because of the overlaying of the outgoing and returning trails. Through the chemo-tactic navigation of other ants following the trail, it becomes incrementally enhanced. Soon all alternatives - the longer routes - are excluded leaving only one short ‘highway’. Such a reliable, flexible and cost saving way of communicating is very instructive for the design of embedded IT systems.

Research in swarm phenomena (e.g. as presented by [13], which is specifically focused on implementation) provides interesting new ways of organizing complex technological systems by letting the order rise bottom-up from the units themselves. What is particularly interesting about swarm phenomena is the possibility of getting corporative behavior relatively cheap and with simple individual constituents. The advance of swarm organization stems from the fact that the difficulty in designing systems is growing exponentially with infrastructural complexity. Deploying a number of simple devices for the same task remedies this by decreasing complexity immensely. Besides swarms (like networks) malfunction much more gracefully because of parallelism and distribution and are generally more robust. Since centralization is getting decreasingly opportune, let alone possible, reliable ways of facilitating global functions is imperative. Swarming seems a promising method.

Like neuronal networks and evolutionary computing swarm intelligence is already widely in use. For example in network switches the model of pheromone trails has been mimicked with great success to handle massive information distribution by optimizing bandwidth usage and preventing bottlenecks.

3.8 Biologically Inspired IT Systems: Autonomic Computing

Several large scale initiatives of systematic applied biological inspiration have been launched the last couple of years from huge players on the commercial IT field. The Autonomic Computing project from IBM is a good example of how biologically inspired approaches to IT design are starting to dominate broadly in IT design [11].[10] The project addresses issues related to ever growing IT systems and the urgent need for creating self-maintaining and self-organizing systems. The goal is to create IT systems that calmly and autonomously take care of maintaining themselves and providing assistance without detailed specifications of all subroutines and solutions. Just like the autonomic systems of higher organisms works in the background leaving more mental energy to interesting and creative tasks, autonomic computing is an initiative to make the time spend with IT meaningful.

The architecture suggested consist of multiple semi-autonomous devices adapting to changing circumstances and needs by following individual (high-level) objectives provided by the programmers. Thus optimized functionality and infrastructure emerges (evolves and develop) by the interaction between users and the systems and among the devices themselves. Though the Autonomic Computing project mainly regards infrastructure issues such evolutionary dynamics are equally important for providing improved assistance at the interface level [2, 3, 4].

4 The Viability of Biomimetics

So far the genealogy of biomimetics reconstructed seems a glorious march toward total victory, but let us pause before this happy ending sinks in too deeply. First of all, the picture appears optimistic because the previous account focused on the genealogy of contemporary biomimetics and deliberately left out most conflicting nuances. Second, because there is no 'end' to history, but only continuous flux, history will un-

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[10] http://www.research.ibm.com/autonomic/

doubtedly move on after a biomimetic heyday. So let us examine the scientific foundation of biomimetics in order to equip it for the productive years to come.

4.1 Biomimetic Considerations: Constraints and Freedom

Generally biomimetics should remain pragmatic and focused with the due self-constrain of a methodology. Naturalism within philosophy and psychology, (the neo-romantic) environmentalism and other tendencies which biomimetic has bloomed together with are by nature ideological. But even if biomimetics does ride on an ideological wave, it is itself only transiently normative as a method to obtain better technology. So ideology should not be its fuel. If biomimetics builds on the slippery foundation of a trend it will most likely vanish together with the trend. Hype, however nice when one is the object of it, must be strictly avoided.

Another concern is the *argumentum ad veracundiam* fallacy; referring to an improper authority. Biology owes a lot of the current attention to the fact that genetics not only has become a hot scientific topic but gained widespread cultural interest as 'the secret code of life'. The resulting 'gene chauvinism' that has dominated most biology the last fifty years, i.e. the intense focus on DNA as the structural blueprint of all life, provided a lot of spotlight - but often for the wrong reasons. The notion of DNA being a blueprint or program for the ontogenesis of the organism, as expressed by daily stories in the news about 'scientist who have isolated the gene for X and Y', has turned out to be overly simplistic [27]. Development is far more complex and non-linearly entangled with the actual environment of the organism. Most developmental biologists are turning towards a system-process approach regarding the functions of genes where genes are not the "selfish" agent of development but merely one, albeit important, *resource* for the self-organizing system [28].

Biomimetics must avoid falling prey for the gene chauvinistic folk biology. The concern is to get seduced into wedlock with the digital architecture by the mutual resonance of molecular biology and computational theory. Even if basing design ideas on conventional digital architectures is necessary as a pragmatic beginning, biomimetics must be careful not to get theoretically tangled up with such linear and/or atomistic approaches. By sticking to an outdated genetic view and merely applying convenient but shallow analogies biomimetics risks getting cut off from alternative paths[11] to new IT. Biomimetics should rest on qualified insight into biology if it nurtures ambitions beyond the metaphorical buzz.

On the other hand biomimetics should not be blindly committed to biological fidelity [29]. First of all because of the unresolved status of fundamental issues within biology itself. To avoid getting sucked into a black hole of biological debate biomimetics needs to practice a cautious pragmatism regarding its biological foundations. Secondly as a design methodology it is committed to take full and creative advantage of the freedom from natural constraints. Biological evolution is heavily path dependant, opportunistically tinkering and myopically seeking merely local optima in the fitness

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[11] Cultural evolution is path dependent - as is its biological counterpart - but by contributing to new conceptual 'scaffoldings' we can influence cultural change and enhance the creativity of future IT design.

landscape. Besides biological evolution is mostly slow compared to other types of developments (e.g. cultural and technological). Hence evolution might be the most efficient *general* adaptive strategy but it can be improved in a range of specific cases by intentional guidance. Biomimetics should strategically capitalize on the most powerful aspects of biological processes and human design respectively.

4.2 Dynamic IT

I hope to have made plausible the general popularity of biology as a consequence of a general scientific movement towards theories of systems, complexity and processes. This development not only describes the historical genesis of biomimetics but - so I will claim - its *raison d'être*. The quest for biomimetics, like its predecessors, is embarking on the challenge of creating dynamic IT. This challenge brings about a lot of changes some of which go to the bottom of our conventional understanding of design. In specific we will need to address a lot of global and long-term issues inherent in dynamic complex systems. And in spite of the temptation to generalize from a specific success instances biomimetics must keep in mind that 'solutions' in nature only seem finished in a limited perspective. Only the meta-solution of adaptive dynamics is universal. Even though copying structural and material configurations will become increasingly important, it will be for their dynamic capacities and not because of solidity, flexibility or other physical characteristics. The intrinsic quality and power of living processes lies in their dynamic capacities. Adaptive processes are continuous 'negotiations' and cannot be conceptualized as solutions. Copying a specific design and implement it in a different setting risks missing the point unless the pragmatic value is clear. What should be the cardinal virtue of biomimetic design is translating the self-organizing capacities of natural evolutionary dynamics into design to facilitate ongoing adaptation and self-maintenance in IT devices [2, 3, 4, 29].

4.2.1 Dynamic Remedies and Dynamic Maladies

In general, biomimetics will address new types of questions arising with pervasive dynamic systems. The characteristics that give such systems tremendously powerful and interesting functionalities also bring along new types of problems: Dynamic systems are vulnerable to dynamic failures. To reverse a famous quote from Martin Heidegger's writing on technology: 'But where the saving power is, grows danger also'. So in the euphoria of creating new types of technology, biomimetic designers must not forget to consider the long term and large scale consequences of such dynamic architectures [29, 30].

In general resilience, oscillation and propagation phenomena will be important issues for the design of dynamic systems. On the positive side to create mutually supportive and robust systems. On the negative to avoid destructive oscillatory or cascading effects. From cybernetics we have learned the importance of dampening feedback functions to avoid chaotic dynamics, and there will be a range of other short- and long-term dynamic phenomena to consider. Dynamic systems are intrinsically path dependent and historic and accordingly biomimetic design will have a strong temporal dimension new to most conventional IT design.

In relation to a general study of resilience and robustness in IT a way of designing ‘immune systems’ dynamically fighting malicious code will be central. Writing in the aftermath of another massive blackout in the US a focus on epidemic effects of large scale and massively interconnected IT systems seems imperative. If we succeed in creating immune systems for IT new issues will emerge. Such immune systems might globally malfunction and give us computer AIDS or even autoimmune defects.

5 Closing Remarks

The living nature is in vogue these years and naturally state of the art technology design is influenced by the trend. However trends come and go as fleeting perspectives on the world and they do not provide suitable foundations for scientific theories. For biomimetics to stand its best chance of contributing significantly to future IT design it must have a clear understanding of its premises and goals. This paper has tried to prepare the ground and provide some of the stones for a better foundation.

I have pointed to the general scientific shift during the 20th century, first manifested by cybernetics and later disseminating to more fields, towards interest in complexity, organization and processes as the main reason for the massive interest for living systems in science, technology and design.

Many factors contributed to this development, the relevant of which this paper has identified. Some of the circumstances that lead to the rise of biomimetics, such as gene chauvinism and environmentalism ought not form basis for a future biomimetic design of IT if the approach is to be more than a historical curiosity. However the scientific reasons for the development towards interests in the organization and dynamics of complex systems do offer valuable guidance for the design challenges ahead. Thus factors stemming from these two different sources should be identified and kept separate in order to avoid a lot of futile lip service.

I have argued that, in analogy with its genealogy, the proper focus for biomimetic IT design is matters of dynamics in complex systems. Mimicking finished designs of nature might indeed be productive for some tasks, but it should not be the focus for biomimetics. The challenge of designing highly dynamic IT calls for models of adaptive self-organizing systems capable of managing on the fly rather than fixed solutions however ingenious. A dynamic approach does not only remedy our limited capacities for predicting future needs and behaviors in complex systems, but is the most adequate response to an inherently fluctuating reality.

Biomimetics is not likely to become, or even if so to remain, the dominant approach to IT design. It is, after all, part of a trend and trends inherently change. However a general dynamic approach to design is likely to dominate more permanently as we learn to master self-assembling, self-organizing, and reconfigurable structures. Biomimetics might fade with scientific progress and the likely unveiling of more universal characteristics ‘behind’ living processes, leaving biology an arbitrary realm of reality to model. Until then our insights into the self-organizing processes of nature nonetheless offer invaluable heuristics for designing dynamic IT.

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