Abstract Life is held together on its various levels — cells, organs (e.g., the brain or immune system), organisms, societies and ecosystems — by general mechanisms of organization, mechanisms that also information technology will eventually have to exploit in order to overcome its complexity barrier. There are good reasons to believe that organization in all its forms can be understood by a common set of general concepts and principles. For various reasons, this topic has slipped through the academic cracks and we don’t have a science of organization, in spite of many isolated relevant efforts and activities. The methodology of physics is very appropriate to take up the challenge. Recent decades have seen a change in perspective on the origin of structure in this world, from hetero-organization to self-organization, but this revolution is unfinished, both in terms of its conceptual development and due to its failure to invade the fields of information technology and molecular biology. The time is ripe to start a new intellectual venture. Due to its great scientific and commercial importance and due to its neglect in classical academic fields, the science of organization is an ideal opportunity for an institute like FIAS.

What is Organization?

Organic systems consist of hierarchies of parts that are functionally coordinated with each other and with the environment. Coordination is achieved by proper design and by a network of interactions, integrating the array of parts into one organic whole. The essence of organization is alignment under a hierarchy of goals. The fundamental goal of life is self-preservation. In the course of evolution, development and learning, however, this fundamental goal is broken down into a rich hierarchy of supportive sub-goals, many of which have taken on a significance of their own. A perfect example of organic behavior is wound healing: I cut my finger, and over the course of minutes, hours and days I can observe my skin and tissues to react in multiple purposeful ways to close the wound, fend off infection and recreate a healthy structure. Important organic structures are living cells, animals and plants, societies of animals including the human society, and ecosystems. Even the biosphere as a whole has been discussed under the auspices of the organic. On several fronts the time has come for a serious attempt to understand the nature of organic structure. Relevant domains are molecular biology, the evolutionary-developmental complex, and the neuro-, cognitive and social sciences. In addition, it would be interesting to clarify the relation of our information technology to organismic structure, perhaps with the prospect of turning dumb automata into electronic organisms. At the confluence of ideas on goal-free self-organizing physical systems, goal-oriented living structures and algorithmically controlled computers lies a research area, perhaps to be called organic computing (see www.organic-computing.org), whose time has come.
Self-Organization

The pursuit of studying organismic structure is fractionated and scattered wide over the academic landscape. There is, however, one important nucleus of concepts that may serve as a starting point for a coherent description. Over the last three or four decades, a silent yet very consequential revolution has swept the world. The issue is the origin of ordered structure in this world. In the pre-revolutionary mind-set, which may appropriately be called hetero-organization, there first must be a complete blue-print for the structure to be generated, and the focus is entirely on the mechanisms of generating the material structure proper. A perfect example for this is Genesis: God first had a clear-cut image in his mind and then took and kneaded the clay to create the world in this image: In the Beginning was the Word. Other examples are the architect’s blueprint on the basis of which the mason creates the house, government and company management by central planning, and computers controlled by programs. The central fault of the perspective of hetero-organization is the suppression of any thought about the mechanisms generating the plan in the first place.

In the post-revolutionary picture there first is a system composed of a large multitude of building elements interacting through elementary forces (a perfect example being the molecules of a liquid). Each building element can be in one of a number of states (e.g., a molecule’s position and momentum), constrained by the elementary forces. Initially, the system is totally disorganized, tumbling through a great many specific states. But under proper control and the influence of the elementary forces, out of this chaos grows a globally ordered state (which in the example would be a crystal, “proper control” meaning cooling below the freezing temperature). States of global order are characterized by optimal harmony between the participating forces, and they win by virtue of their greater staying power, which is due exactly to this optimal inter-locking of the local forces. One speaks of a collective effect. Besides crystals and more generally phase transitions, self-organization has been discussed in connection with convective pattern formation on all scales — from the coffee cup to the Earth’s atmosphere, oceans and crust —, laser action, star and galaxy formation as well as social systems. In distinction to hetero-organization, the equivalent of a plan arises in self-organization at the end, not the beginning: In the Beginning there was Chaos.

There are deep roots to the ideas of self-organization. Frankfurt’s child Goethe certainly had this perspective, evident already in these lines of Faust’s initial monologue:

Wie alles sich zum Ganzen webt,
Eins in dem andern wirkt und lebt!
Wie Himmelskräfte auf und nieder steigen,
Und sich die goldnen Eimer reichen!

Through the ages, many have marvelled at the beauty of the dynamical and geometrical forms created by self-organization, see, for example (Thompson, 1961; Schwenk, 1962), and have speculated about the general mechanisms producing them (Weiss, 1967). Self-organization became a coherent movement in the late 60ies and early 70ies through the
The Unfinished Revolution

The revolution started by the ideas of self-organization is unfinished in a dual sense. Neither has the revolution taken hold of all fields of endeavor it should have transformed, nor are its concepts fully and adequately developed. Much resistance (well-justified at that!) to self-organization as conceptual framework for organismic or cognitive organization is caused by its failure to properly incorporate goal orientation. When it comes to methods of optimization, the “cost” or “objective” or “energy” functions that do formulate explicit goals are defined in the hands of the scientist, not the system. Moreover, single, undifferentiated goals are totally insufficient to do justice to the issue. Life may have started, a long time ago, with the single and fundamental goal of self-preservation, but all living organisms have long since incorporated hierarchies of secondary and tertiary goals, hierarchies that themselves are subject to self-organization. Indeed, we humans spend a good part of our life trying to keep our goal hierarchies in order and free of contradictions; helas not always successfully.

Another, grossly underdeveloped aspect of self-organization concerns the mechanisms needed to regulate control parameters. Systems often contain many of them, and their values typically have to hit certain windows in order for the system to organize properly. Moreover, any major transition in the organized state is likely to require re-adjustment of control parameters. Given the typically large number of these parameters, blind search is out of
the question for the most part, and there must be regulatory mechanisms pushing parameters in the right direction. These mechanisms presumably are to be based on some very fundamental and general goal definitions characterizing organized states. Finding these is a scientific goal of the utmost importance. One possibly relevant idea sees the organized state as poised at a delicate balance between boring stability and senseless chaos, see work on self-organized criticality (Bak, 1996). If this is so, it is still an open question how to quantify the state of a system (and its subsystems) along that axis. Much more conceptual work will have to be done on this front.

The list of unfinished work doesn’t end here. Differentiated organized states are never created in one step. The ontogenesis of an organism, for instance, proceeds in cascades. The initial symmetry of a homogeneous cell or piece of tissue is first broken by establishing polarity and some gross coordinate system. This first step of organization creates the arena in which a second process adds more detail, creating itself the boundary condition for yet another round or organization, and so on through many stages, each creating more detail than the previous and affording the fixed boundary conditions for the next. A pale shadow of the phenomenon shows up in some hydrodynamic systems (Bénard or Taylor flow, Koschmieder, 1993), but these are not ideal paradigms for several reasons, one being the very fluidity of the boundary conditions set up by one stage for the next, giving way too easily to turbulence. The task of developing the necessary conceptual tools to describe cascades of organization is daunting. Stability analysis, the work horse on single-step self-organization, has been practical so far only if the initial boundary conditions are simple (free space, periodic, circular or spherical boundary conditions) and the ensuing function systems can be found in the handbooks of applied mathematics. If, however, the boundary conditions themselves are already the result of several stages of a cascade, whole new mathematical function systems would have to be designed. Numerical methods may help to define these specific patterns, but the ultimate goal must, of course, be a conceptually and analytically explicit structural theory for the universe of organic forms that can arise from these cascades of organization.

So far, attention has been focused on the generation of spatial (and, although to a much lesser extent, temporal) patterns — pretty pictures, so to speak. This is natural when the building elements are spatially localized and compact and interact on the basis of spatial neighborhood. Life has, however, created interaction systems no longer dominated by short-range physical contact between elements. This applies, for instance, to molecular signalling in the cell, neural signalling in the nervous system and to the interaction of individuals and species in societies and ecosystems. New concepts will have to be found to describe the organized patterns that arise in such systems.

Organized systems are composed of sub-systems, of compartments, with tight functional coupling within and more loose coupling between. The organized state is characterized by coordination of subsystems under common goals as well as coordination with the environment (which itself might be a super-organism). A prime example for this is the brain’s state of consciousness (Malsburg, 1997). Organizing systems have the inherent tendency to increase coherence or coordination in this sense, or to re-establish it after disturbance.
They do this autonomously, without the intervention of extraneous agents endowed with insight and foresight (a remark whose significance will probably only become apparent further below). The terms and conditions for the coordination of subsystems are still largely in the dark. All we have so far is descriptions of specific, detailed cases, without obvious general principles uniting them.

**The Unity of Organization**

Several more such open fronts can be described, but these examples may already drive home my point that the revolution is unfinished on the conceptual front. As already mentioned, the revolution is also unfinished in the sense of not having reached and transformed several susceptible sectors of human endeavor. Before I come to these, a fundamental issue must be addressed. Are the different phenomena that we perceive as organized — the living cell, the living organism, its immune and nervous systems, ecosystems, civilization, aspects of a future information technology based on organic computing — governed by fundamentally different mechanisms without any internal connection, or are essential aspects common to them such that “organization” can be considered a fundamental, coherent phenomenon that will eventually be described by one coherent set of concepts?

Here is an argument speaking in favor the general applicability of at least a core of mechanisms. It is based on the tremendous flexibility of certain structures in dealing with new situations of very different kind. Recent discoveries in molecular biology are making it clear that the “genetic toolkit”, the array of interacting genes responsible for the control of animal ontogeny, has been preserved in astonishing detail over hundreds of millions of years and across profound structural differences between organisms (see, for instance, Carrol, Grenier and Weatherbee, 2001). Thus, essential arrays of genes regulating the establishment of body plans, e.g., the so-called homeobox genes, are preserved in essential ways over vast evolutionary domains, although the Bauplan of the taxa involved can be very different. Moreover, even very variable detail of individual species is determined by gene structures that are highly conserved in basic structural aspects. A striking example is the gene for inducing eyes, which we share with insects, molluscs and worms although the structures of their eyes are fundamentally different from each other and ours. Consequently, in spite of the great structural differences between all the taxa involved, there seem to be deep organizational aspects common to them all.

Another example of organizational flexibility is civilization. Homo sapiens has evolved for life in small groups, not much larger than a hundred individuals. Yet, within a mere ten to fifteen thousand years man developed the phenomenon of civilization, by now involving hundreds of millions of individuals in hierarchical structures of tremendous organizational depth. Our individual mind is very far from understanding these structures and certainly cannot be held responsible for creating their global aspects. Nor are these structures in any concrete sense implicit in our genetic makeup. These structures were neither designed nor evolved. They just grew. There is a message here: only mechanisms of a very general kind can be held responsible.

A tightly related issue is that of the flexibility of the individual human mind. Although
not evolved for it, we play chess and piano, drive cars, fly planes, do mathematics and philosophy. The essence here is that the human brain, confronted with new problems of a wide variety, is able to come up with solutions to them. For new problems there are no solutions on the shelf, by definition. The only way they can be solved is by recourse to general, fundamental strategies. The problems of this class can obviously be embedded in a hierarchy of more general structural descriptions such that individual solutions can be generated at affordable procedural cost. Our success and experience show that this class of problems is rich and interesting. By extension, the phenomenon of organization may be limited to a universe of structures of a specific kind, structures that can be produced by efficient methods and that are rich and interesting. The issue at hand is to explore and characterize that universe and the procedures by which to navigate in it. Surely life occasionally had to go beyond that universe, by evolving specific solutions to specific problems the hard way, by blind search. We see the result in the form of devices, such as the molecular machines for photosynthesis, photo detection, proton pumping or muscle action. Once found, life may hold on to these inventions over billions of years. Organization may be seen as a set of general mechanisms to put these special devices in action at appropriate places and times and in appropriate combinations. For another voice in favor of a universal view on organization see Kitano (2001).

The Missing Academic Field

If there is the potential for a coherent scientific venture around the theme of organization, the existing academic fields have failed to recognize it, each for their own reasons and prejudices. Not that there aren’t live activities addressing relevant issues. Examples are what is called complex systems, artificial life, animate robotics, soft computing in its various forms — neural networks, fuzzy logic, evolutionary algorithms or genetic programming —, belief propagation, autonomous agents, catastrophy or bifurcation theory, various brands of optimization and probably many more. But all these ventures are too timid to attack the central issues, are disconnected, focused on sub-problems and -systems rather than whole systems or too abstract and disconnected from particular applications, and they all live on the fringes of whatever academic field they are situated in, more suffered than supported, never considered part of the core of their department’s activity and curriculum.

To say it briefly, the reasons of the relevant academic disciplines to not consider the phenomenon of organization as central to their business are that biology is too focused on facts and detail at the expense of general principles, physics is too conservatively sticking to its classical application domains, and computer science is too much committed to the algorithmic division of labor between man and machine, remaining totally in the fangs of the concept of hetero-organization.

Neuroscience and cognitive science are most directly confronted with the phenomenon of organization, for the reason given above. They and their forerunners certainly have assembled the richest treasure of relevant insights, concepts and perspectives. Yet the drives for fact hunting and professional specialization tend to keep the field from devoting more attention to the fundamental issues, concerning, for instance, the representation of mind states by brain states, the mechanisms of brain state organization, the learning
from the natural environment and the \textit{in silico} realization of central functional processes such as learning, perception and motor control. This latter activity has not yet attained the status and recognition it deserves. Computer simulation is a very powerful tool for searching through piles of functional ideas and theories for those that can actually be made to work under realistic constraints. The time has come for neuroscience to assert itself as a model for information technology, by establishing a live feeding chain from \textit{in vivo} experiment to conceptual formulation to functional demonstration in the computer.

In molecular biology a wealth of new powerful techniques is leading to a tremendous speed-up of discovery. We see at present the birth of the new field bioinformatics, whose specific aim is the administration of the this wealth of information in terms of data base and internet tools. Whole genomes, including man’s, are deciphered or will soon be deciphered, and avalanches of information about signalling networks and the structure of the immune system are pouring in through hundreds of published papers a day. Now it starts to hurt that for decades the field has neglected to build up an academic infrastructure to develop the conceptual tools for understanding the regulation and organization of networks of thousands of interacting molecules. With microarrays it is now possible to observe, for example, the up- and down-regulation of scores of genes when a yeast cell reverts from aerobic to anaerobic metabolism, but the interaction patterns initiating and coordinating this reorganization remain totally in the dark. There have always been voices pointing out the necessity of theoretical work (see, e.g., Malsburg, 1985; Weiss, 1967; Brenner 1997), but only in the last couple of years the field as a whole has started to realize the need for action (see, e.g., Allen, 2001; Kitano, 2002; Csete and Doyle, 2002; Bower and Bolouri, 2001). Many human ailments, such as cancer or disorders of the immune or nervous systems, cannot be understood on the basis of single genes or molecules, involving, rather, the organization of complex molecular networks, and they will never be cured without understanding those networks. Just as with the brain, new concepts have to be developed to understand the implementation of purposeful and reliable reaction chains among graded signals: organic computation.

The central knot of life is the evolutionary-developmental machine, the genetic regulatory network that is responsible for controlling organismic ontogenesis, the piano on which evolution plays. Darwin’s theory of evolution can be seen as one of science’s earliest credos for self-organization, yet the conceptual gap between the simple idea of mutation and selection on the one hand and the creation of such marvellously purposeful structures as wings, hands, eyes or brains is still so gaping wide that one can hardly be surprised at the widespread resistance that Darwinism is still meeting — even among scientists! Also computer programs evolve by local modification and testing, but that description hardly does justice to a process that is highly structured — by repeated patterns, structural inheritance, nested hierarchies and much more. There are first signs already that life has endowed its evolutionary-developmental machinery with at least as much structure, accelerating evolution, the ability to evolve rapidly being itself one of the traits with selective advantage for a group of species (Malsburg, 1987).

Molecular biologists often express the opinion that the time has not come yet for theoretical
work, as so much detail is still unknown. The truth is that we will never have enough molecular information to be able to simulate it on the computer in any direct sense, and the essential structures will never be found by mere data mining (Allen, 2001). There are just too many molecular species and tertiary structures, too many molecular aggregates and rate coefficients, too much uncertainty in the data even when they are in. The only savior for biology (just as for life!) can be general patterns that assert themselves in spite all variation of detail, and the only way these patterns can be found is by imaginative work and analogical thinking. A very potent argument for this view is the work of Hans Meinhardt (1982), whose modeling of ontogenetic processes in terms of reaction-diffusion equations predicted many genes and structures that have later been found, including the oscillator mechanism for producing metameric somites in vertebrates. A similar convincing demonstration of the power of theoretical arguments is the late Arthur Winfree’s work on biological clocks (1980, 2001) and in particular its application to heart fibrillation, a problem of prime medical importance. Both pieces of work would not have been possible without intimate knowledge of large masses of relevant biological detail, but the ultimate basis for success was reference to general concepts of space and time, structural stability, hierarchical structure and others, constraints that life itself has to obey.

Computer science is still basking in the grandiose success of the information technological revolution, whose momentum seems unbroken, with Moore’s law doubling chip complexity every year and a half on and on. However, there are clouds on the horizon. The complexity of structures, both hardware and software, is beginning to let computer science’s concepts come apart at the seams. Large software projects already have a 30% likelihood of complete failure (Gibbs, 1994), and a recent study by the US National Institute of Standards and Technology (NIST, 2002) came to the conclusion that the software crisis is costing the US economy alone $60 billion annually, not counting ripple effects which may run up to a multiple of that figure. Also the complexity of computing chips is starting to be a problem. Intel had a team of 800 engineers to test its latest chip design and sees it as a serious problem of the future to prevent functional failure due to complexity alone. With very few exceptions, academic departments of computer science are totally oblivious to this crisis, teaching a curriculum that fails to prepare students for the problem of coping with large evolving software and hardware systems. The venture of Artificial Intelligence, conceived entirely within the confines of the algorithmic division of labor and dependent on human insight into the particularities if individual applications, can no longer be seen as the solution of these problems (just let me remind the reader of the grandiose failure of Japan’s Fifth Generation Computer project, which was based on this idea). Computer science can live up to its epithet of “science” only by developing a conceptual framework that turns mindless automata totally dependent in their function on detailed human insight into electronic organisms guided by nothing but general goals, goals that are, of course, defined by humans. Today, the computer is seen as the ideal slave, doing exactly what being told, and that at blinding speed. It is now turning out that there is a very serious problem with this: the computer also has to be told its every move, down to the minutest detail. This chore of programming is at present eating up a substantial chunk of human intellectual energy.
Digital machines, taken as physical devices, have no inherent tendency to order and have no representation of goals. Instead, they totally depend on the algorithmic division of labor. Humans alone are in the possession of all the creative infrastructure necessary for the creation of functional computing structures: Goals, methods, world knowledge, interpretation and diagnostics. This is pure hetero-organization. Computer science is giving no thought to the mechanisms leading to the plan — the program —, only to the mechanisms and conditions of its execution. This attitude is often justified with the argument that we humans have to keep the reins in our hand and cannot permit the computer to follow its own goals. Ironically, one must observe that even now, with computers under strict algorithmic control, the reins are slipping from our hands. Computers do not always do what the user or customer, or even the programmer, has in mind, simply because the scores of thousands of people that have written the software interacting within a single application can no longer be coordinated, even if they had a common set of goals (which they don’t, as the example of viruses shows). The growing flood of abuse, of system failures and misadaptations that we experience in the computing world will eventually be stemmed only if computers are restructured as electronic organisms, guided by general organizational mechanisms and a set of goals that humans have defined. Only by direct on-line surveillance and interpretation of the ongoing process in the light of established goals can machines be made safe and functionally reliable. The task of defining goals is not trivial at all, and it is time society took hold of it instead of letting itself be held in tutelage by a priest cast of software specialists.

For near to two centuries, physics has managed to be the fountain head of novel technology, by developing mechanics, thermodynamics, electromagnetism and quantum mechanics. For a long time, engineering could count on a solid scientific basis for its innovations. Now, the situation is fundamentally changed. Information technology, and more generally the management of complex systems, have to go out on a limb without a pre-existing scientific basis for their venture. At the same time, students are running away from physics, going where they expect the future to be made, in biology and information technology. It is time that physics began to see the pattern and started to take up the challenge of developing a science of organization. Methodologically, physics is well prepared. Its central strategy is to identify and work out paradigm cases, like free fall, two-body motion, the hydrogen atom, the ideal gas, the Ising model of magnetism, and so on. In doing so it lets itself be guided by the instinct that the essence of broad ranges of phenomena can be captured and understood in terms of essentially simple concepts. There is no reason to believe that this approach will not work vis-à-vis the phenomenon of organization. Academic physics departments that resolved to focus on the subject would become great attraction points for the inquisitive minds of the generation, both students and faculty. And it is likely that the subject of organization would be a fertile source of inspiration for established fields within physics, including particle physics and cosmology.

**Conclusion**

It is not clear why the revolution discussed here has stalled. Maybe the pressure to specialize was too overwhelming, maybe the theoretical difficulties too big. In any case
there seemed to be no urgency to the matter, as biology and technology evidently were on
the right path to progress. With the approaching complexity barrier, both in molecular
biology and in computing, this may be changing now and the need to understand the secret
behind life’s organization becomes too obvious to be ignored much longer. The erstwhile
arrogance of computer science vis-à-vis brain-inspired approaches to technology is coming
around with a vengeance.

Academic fields are notoriously inert, perhaps due to curriculum constraints and self-
preservation of fields of study leaving no space for novel activities in times of shrinking
budgets. Appointments of faculty for themes concerned with the study of organization on
its proper level are rare and far between. Here is a golden opportunity for an institute that
is free of historical burden, yet can draw on resources and students from existing institutes
and academic departments. Although it will not be easy to have senior scientists commit
to non-tenured positions, it should be possible to attract visitors for shorter or longer
visits, creating a fertile atmosphere of mutual inspiration. And if the institute manages
to establish fame, young scientists will make it a point of honour to spend their doctoral
or post-doctoral time there. Young scientists may receive essential intellectual impulses at
the institute for their life’s work. The existing ideas concerning organismic structure are
scattered wide accross fields and are in dire need of being collected and conveyed to new
generations of researchers. What better place for this purpose than an institution standing
apart from the established fields yet close enough to them to get inspired and contribute
to their curricula.

Although one will have to think in terms of time scales on the order of a couple of decades,
it is probably hard to overestimate the beneficial impact a science of organization will have
on science, economy and society and our image of ourselves.

Information technology is rushing headlong into a complexity barrier from which it can
be saved only by following the model of life’s organic structures (cf IBM’s initiative on
autonomic computing, researchweb.watson.ibm.com/autonomic/manifesto). The equiva-
lent of software should be grown, instead of being written in a tedious and costly process
wasteful of intellectual man power. The mechanisms of evolution, development, adapta-
tion, learning and teaching should be harnessed for the purpose creating artificial organic
computing structures able to quickly adapt themselves to our individual and collective
needs. On the creative side, human involvement should be restricted entirely to defining
and communicating goals and to teaching by way of example.

Life on earth is first and foremost a molecular affair. It is molecular interactions that
define the cellular repertoire of behavior, which in turn is shaping the structure of cellular
cooperatives, organisms. Understanding the molecular interactions at the base of life, not
as a senseless tangle of separate reactions but in terms of the coordinated whole that
it really is, will finally help us to get rid of genetic deseases and to overcome even those
ailments, such as cancer and disorders of the immune system, that involve many interacting
genes and molecules.

The perhaps most profound influence on our life a science of organization may exert is
by letting us better understand ourselves individually and collectively. The very center
of our existence is the brain process at the basis of our mind, and a clear understanding
the way brain states correspond to our inner experiences and how they are organized
will not fail to have deep consequences for the way we see ourselves and the world. A
better understanding of the mechanisms of learning might help to improve our educational
system significantly. The sciences have always prided themselves staying aloof of value
considerations. This attitude cannot be maintained when studying organization. Our
lives are deeply affected and structured by our goal hierarchies. These do not fall from
heaven, they are themselves formed by webs of interaction within themselves and with
biological and societal processes. We should better pay attention to what the scientific
method has to contribute to the subject. The complex society of modern civilization has
not been formed by revelation nor by design through individual minds but has grown on
the basis of universal mechanisms that were also responsible for the growth of molecular
collaboration in the cell and cellular collaboration in the organism and will hopefully soon
employed for directing the growth of computing structures. These mechanisms are worthy
of study.

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