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Principles of Biological Autonomy

Francisco J. Varela

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*To the loving kindness of
Raul Varela and Corina Garcia,
sine qua non.*

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Preface

Information and Control Revisited

“Les systèmes ne sont pas dans la nature, mais dans l’esprit des hommes.”

C. Bernard, *Introduction à L’Étude de la Médecine Expérimentale* (1865)

“Was wir liefern sind eigentlich Bemerkungen zur Naturgeschichte des Menschen; aber keine kuriose Beiträge, sondern Feststellungen von Fakten, an denen niemand gezweifelt hat, und die dem Bemerkwerden nur entgehen, weil sie sich ständig vor unsern Augen herumtreiben.”

L. Wittgenstein, *Bemerkungen über die Grundlagen de Mathematik* (1956)

Two themes, in counterpoint, are the motif of this book. The first one is the autonomy exhibited by systems in nature. The second one is their cognitive, informational abilities.

These two themes stand in relation to one another as the inside and the outside of a circle drawn in a plane, inseparably distinct, yet bridged by the hand that draws them.

Autonomy means, literally, self-law. To see what this entails, it is easier to contrast it with its mirror image, allonomy or external law. This is, of course, what we call *control*. These two images, autonomy and

control, do a continuous dance. One represents generation, internal regulation, assertion of one's own identity: definition from the inside. The other one represents consumption, input and output, assertion of the identity of other: definition from outside. Their interplay spans a broad range, from genetics to psychotherapy.

We all know control well; it has been charted out and formalized. Hence the power of the computer and of consumer-oriented services. Its popular model is: something in/process/something out. We stand on both sides of in and out, whether an economic system, a compiler, or a person's mind. The fundamental paradigm of our interaction with a control system is instruction, and the unsatisfactory results are errors.

Autonomy has been less fashionable. It is usually taken as a more vague and somewhat moralistic term, and waved off as a question of indeterminacy. There is little understanding of its generic import, let alone its representation in formal terms. The fundamental paradigm of our interaction with an autonomous system is a conversation, and its unsatisfactory results breaches of understanding.

One fundamental intention of this book is to bring the *interplay* of these two notions into the open, and to identify the underlying mechanisms that endow natural systems with autonomy. As it turns out, these mechanisms have to do with the pervasive circularities to be found in nature. We are led to consider in all seriousness the traditional image of the snake eating its own tail as the guiding image for autonomy as self-law and self-regulation. But what does this "self" mean, more precisely? A focus on this question is a guiding thread throughout this book, leading us to a characterization of self-referential, recursive processes and their properties as fundamental mechanisms of natural autonomy.

The way a system is identified and specified through our interactions with it is not separable from the way its *cognitive* performance is understood. The control characterization is intimately tied up with an understanding of information¹ as instruction and representation. Accordingly, to explore the way in which a system specifies its own identity is *also* to explore what its informational actions can possibly mean (Piaget, 1969). Thus, by discussing autonomy, we are led to a reexamination of the notion of information itself: away from instruction, to the way in which information is constructed; away from representation, to the way in which adequate behavior reflects viability in the system's functioning rather than a correspondence with a given state of affairs.

It can be said that the central line of thinking in this book is to untie, explicitly, the knots of this inseparable trio: a system's *identity*, its per-

¹ I use here the word information in its most generic sense of *semeios*. Other connotations that the word has acquired in its Shannonian treatment are here strictly secondary. See for a discussion the excellent work of Nauta (1972), *The Meaning of Information*.

formance in its *interactions* with what it is not, and how we *relate* to these two distinct domains. Different preferences and values attributed to this triad determine how we see a system, how we conceptualize information, and what role we attribute to ourselves in the whole process.

Stated in another way: Behind the predominant views on control and information-as-representation, we find a constellation of philosophical assumptions shaping the way we relate to the diversity of sentient beings.² By these I mean entities to which we are compelled to acknowledge an informational side, a mind of sorts, however opaque and simple. I am not talking about individual living beings only, but of many other aggregates such as ecological nets, managerial complexes, conversations, animal societies—in fact, wherever there is a sense of being distinct from a background, together with the capacity to deal with it via cognitive actions.

Since most of our lives is concerned with how we see other entities and how we comprehend what transpires between us, it is no wonder that the information sciences, understood in this broad sense, are loaded with philosophical and ethico-political connotations. It is my view that this area of science has been substantially modeled in the image of physics and its technological pathos. One essential difference here however is that *we* and the world that support us belong to the categories of sentient being and not of atoms and quasars. Consequently, the Promethean approach inherited from physics bounces back at us in a fast and dramatic way.

I am not being grandiose. The fact is that, after the Wars, scientific imagination turned from watts to bits, and in almost no time produced a dramatic change not only in the shape of what scientific research was about, but in the life of everybody as well. As if in a boiling pot, the images of information and information processes surround everybody and everything that has an interest in complex relationships, communication, and mind. Ideas, fields, and applications crisscross, and there is no sense of direction or unification such as the prewar science seemed to have. I am not seeking such unification here at all. I am instead identifying a *dominant assumption* that seems pervasive at every depth of this boiling pot, and I am proposing to explore an alternative.

Rosenberg (1974) has aptly characterized the dominant view of the information sciences as the "gestalt of the computer." He is right, I believe, in a double sense. First, it is indeed like a perceptual gestalt in the sense of a favored perspective, making it very hard to step outside

² A third and last member on this constellation of concepts is that of *subject*, as is understood currently in the image of a skull-bound individual. I will not enter in this book into the discussion of this central theme, although a few points are touched upon in the last chapter.

to contemplate where one is standing. Second, the computer indeed embodies the metaphor in terms of which everything else is measured. The fast pace in the field of design with its inherent manipulative ethos has overshadowed every other source of images and modes of understanding. Information, for the computer gestalt, becomes unequivocally what is *represented*, and what is represented is a *correspondence* between symbolic units in one structure and symbolic units in another structure. Representation is fundamentally a picture of the relevant surroundings of a system, although not necessarily a carbon copy.³

From the point of view of the natural (including the social) systems, the computer gestalt is, to say the least, questionable. There is nobody in the brain to whom we can refer to obtain an assignment of correspondences, and any attempt to view it as an input-output processing machine can be equally well interpreted as the machine's reducing *us* to an equally allonomous entity. With any of the variety of natural, autonomous systems, all we have is certain behavioral regularities, which are of interest to us as external observers having simultaneous access to the system's operation and to its interactions. Such regularities, when we choose to call them cognitive and informational, always refer us back to the unitary character of the system at hand, whether a cell, a brain, or a conversation. From this perspective, what we call a representation is not a correspondence given an external state of affairs, but rather a consistency with its own ongoing maintenance of identity. Such regularities, which we choose to call *symbolic*, are *not* operational for the system, for it is *we* who are establishing correspondence from a vantage point that is not in the system's operation. Thus, when we switch from a control to an autonomy perspective, what we call information differs from the computer gestalt in important ways. Every bit of information is relative to the maintenance of a system's identity, and can only be described in reference to it, for there is no designer. In this sense information is never picked up or transferred, nor is there any difference whatsoever between informational and noninformation entities in a system's ambient.

Useful as it may be in the fields of design, the paradigm of cognitive processes as representations has been given a privileged status in our current thinking about cognition. It is well and good that we can sidestep these distinctions in the domain of design, or in some of our dealings with natural systems where there may be treated analogously. To take this approach as a *general* and universal strategy for all aspects of natural systems, including human transactions, seems incredibly limiting. In fact, it is not workable at all, as I shall argue in detail for the two richest cognitive systems in living beings: the immune and the nervous networks.

³ Thus according to Newell and Simon (1976), this should be one of the basic building axioms of the information sciences.

It is one of those interesting *corsi e ricorsi* of the history of ideas that the source of the computer gestalt was an understanding of living systems. From this initial inspiration, however, most of the emphasis seems to have shifted towards engineering and design, far more than into other areas. I am arguing, *again on the basis of biological systems*, that this predominant understanding is one-sided and incomplete.

I am claiming that information—together with all of its closely related notions—has to be reinterpreted as codependent or constructive, in contradistinction to representational or instructive. This means, in other words, a shift from questions about *semantic* correspondence to questions about *structural* patterns. A given structure determines what constitutes the system and how it can handle continuous perturbations from its surroundings, but needs no reference whatsoever to a mapping or representation for its operation. We don't ask what is the correspondence between an animal nervous system and "the" world in which it is, but rather what is the structure of the nervous system whereby it can effect shaping of its domain of interactions. The notion of information as representation is ultimately independent of the system's structure; but it is for the external observer—better still, for the whole tradition describing the situation—that the externality of the supposed world to be mapped exists at all. By insisting on looking at cognitive processes as mapping activities, one systematically obscures the codependence, the intimate interlock between a system's structure and the domain of cognitive acts, the informative world which it *specifies through its operation*. Informational events have no substantial or out-there quality; we are talking literally about *in-formare*: that which is formed within. Information appears nowhere except in relative interlock between the describer, the unit, and its interactions.

This idea is not really new; it has been familiar to many scientific and philosophical traditions. However, under the towering influence of positivism, it has been ignored in the language and empirical research of science by engineers, biologists, and educators alike. My argument takes root in science and attempts to redress this imbalance from the inside. This shift from a semantic to a structural point of view is, at this stage, a research program that is only beginning to unfold. In this book I shall explore and give substance to only a few items of this program. But unless we take into account that there is an autonomous side to many natural and social systems, we run into troubles, not only in the specifics of research and formalizations, but in the wider scale of our dealings with sentient beings, with life, with the environment, and in human communication. In this respect, the problems of biology are a microcosm of the global philosophical questions with which we grapple today.

One basic tenet in these pages is that I am not *against* what I have called the computer gestalt, nor am I rejecting it as useless. I am saying

it is *limited* and workable only in situations of restricted autonomy and fixed in-formation, which are actually the only situations where control and representational views can emerge at all. The perspective I am sketching here can accommodate this standard view, and set it more in balance. Accordingly, one very important concept throughout this book is that of complementarity, and the constructive interplay between two interdependent visions that raises one's level of understanding to a new level. I am not an "autonomist" at war with control engineers; but I do want to state clearly that the control view, if taken alone, leads to inadequacies in our understanding of natural systems, and to important epistemological and political difficulties. I am not saying what is better; I am stating alternatives.

The fact that I take here the point of view of a natural historian (and a biologist at that) means also that there is no discontinuity with the way in which these concepts can be seen to apply to man's cognitive capacities, and, for that matter, to societal dynamics. What we see operating in greater detail in natural autonomy—the actual subject of this book—is a reflection of what we ourselves are immersed in.

In strict accordance with this view of in-formation, we shall see that the presence of the observer (of the observer-community, of the tradition) becomes more and more tangible, to the extent that we have to build upon a style of thinking where the description reveals the properties of the observer rather than obscuring them (as von Forster has aptly remarked). It is a view of participatory knowledge and reality, which we see rooted in the cognitive, informational processes of nature from its most elementary cellular forms. There are, in fact, two distinct ways in which the irruption of the observer becomes apparent in this presentation.

On the one hand, we see the necessity of acknowledging the role of the process through which we distinguish the unities or entities we talk about: the way the world is split into distinct compartments, and the way such discriminations and distinctions are related by levels and relationships between levels. Thus, the maintenance of a system's identity—its autonomy—is a distinct and irreducible domain with respect to the functioning of that system in its interactions. These two phenomenal domains are related only through *our* descriptions, and these relationships do not enter into the operation of the system we are concerned with. Each of these views is complementary to the other, and we need to make them explicit.

A second way in which the observer enters into this view of unities and their information is that we ourselves fall into the same class—there is continuity in the biological sense, and in the cognitive mechanisms that operate elsewhere in nature. Thus what is basically valid for the understanding of the autonomy of living systems, for cells and frogs, carries over to *our* nervous system and social autonomy, and hence to

a naturalized epistemology, which is not without its consequences. It forces us to a renewed understanding of what physical nature can be that is inseparable from our biological integrity, and what we ourselves can be that are inseparable from a tradition.

In point of fact, these two modes of bootstrapping the observer-community close the circle for this presentation and make it hang together cohesively. It embodies, once again, the same basic notion that a useful perspective does not require an objective, solid ground to which everything can be finally pinned down. The flavor of the epistemology espoused here, and assumed by the structure of the book, is that knowledge is indeed quite full of detail but hangs nowhere, apart from its tradition, and leads nowhere except to a new interpretation within that tradition. I believe that the importance of coming to grips with this realization, demanded by current research and by logical rigor, is momentous in science, ethics, and personal life. If these pages contribute an inch to that awareness, they will have succeeded amply in my eyes. Yet I immediately reiterate the caveat that I shall *not* dwell in these matters in great detail. My subject is autonomy in natural systems. All the connections and implications with epistemology and human affairs will be pointed at, but not explored at any length.

There are certain persons who have influenced this book so pervasively that it seems fair to mention them at the outset. They are Humberto Maturana, Heinz von Foerster, Gregory Bateson, and Jean Piaget. Of all of them, only Maturana is truly represented in the content of these pages. What has always inspired and maintained my interest in these thinkers is that they refuse to set lines of demarcation, and yet keep a fixed gaze along a line of thinking. Thought comes alive, and it enlivens the stillness of disciplines. Further, all of them make natural history a permanent source of observation; there is concern with contemplation rather than design. A third trait common to these men, and of great importance to me, is the presence of an experimental epistemology as an explicit background to consider information and mind in its fullest sense, be it in Balinese dance or frog's vision. This breadth of concerns, embodied in delicate interplay between a view of the general and the texture of the specific, is what seems to be called for.

I have tried not to be idiosyncratic in my use of language, and sparse in introducing new nomenclature. Yet it seems inevitable to introduce a certain number of new concepts and definitions if one is to point to an uncharted ground at all. Thus, for example, I could have couched the discussion of autonomy in terms of whole systems or totalities, but these notions have acquired many connotations which might have obscured what I wanted to say; this pitfall, in fact, lurks throughout the book. Pointers and cross-references are provided in every case to related literature.

The text unfolds in three parts. These cover, respectively: autonomy of living systems as a source of characterization of autonomy in general; forms of representing complementarity and circularities; and the cognitive capacities of autonomous system and their codependent information. Each one of these parts can be read somewhat independently of the rest, according to the reader's inclination.

I cannot say too strongly that this book is offered in the spirit of synthesis and exploration, not of treatise, dogma, or set opinion. Nothing presented here can be regarded as fixed, and I am well aware of it. In fact, the very nature of the subject, of sketching a gestalt switch about natural information and control, is predictably intricate and likely to yield mixed results. It involves partly a reinterpretation of what seems already available to us, conceptually and experimentally, and partly a rather difficult process of conceiving new designs and adjusting to new perspectives. The whole thing is actually quite shifty. My rationale for publishing it is that there is *enough* here to start and liven a discussion, enough of a body of work to create debate. I simply look at all of this as signposts in a vast shapeless landscape, where many routes may be taken, and perhaps, where we may choose to return to where we started with the feeling of seeing it again, more sharply.

Acknowledgments

I have been extraordinarily lucky in enjoying the teachings and intellectual brotherhood of very many people. Many thanks go first and foremost to my friend and former teacher Humberto Maturana. Second only to him, I am deeply grateful for what I have learned from Gregory Bateson, Fernando Flores, Joseph Goguen, Ivan Illich, Chögyam Trungpa, and Heinz von Foerster. There are many other friends and colleagues whom I will not list here, but to whom I am equally in debt. Perhaps more than to anybody in particular I owe to the collective mind of the people of Chile, where I found my inspiration.

The initial stages of this work were carried out at and with the support of the University of Chile. It continued at the Universidad Nacional in Costa Rica, which generously housed me in the difficult period after I left my country torn by civil war. A major portion of this book was produced while I was with the School of Medicine at the University of Colorado. I am indebted to David Moran and David Whitlock for giving me ample freedom there. The final stages of writing were carried out at the Institute of Behavioral Science, University of Colorado at Boulder.

Financial support came out of grants from the National Science Foundation (BMS-73-06766, jointly with D. Moran), and the Alfred P. Sloan Foundation, who made me one of their fellows for 1976–1978. Finally, thanks are due to George Klir for his encouragement and enthusiastic editorial efforts.

This book is based on work carried over a period of eight years of concern with the central questions of autonomy and in-formation. A basic motive for writing it was the feeling that it was time to pull the disparate threads produced during this time a bit closer, and to offer a panoramic view of where I am trying to look. Except for a few chapters, all of the

material included has been published before. I have reworked and re-written all of these source papers extensively, and added whatever connecting links seemed missing at this stage. In spite of this, the reader will have to bear with a certain amount of repetition and differences in style. Many of the source papers were written in collaboration with other authors: Joseph Goguen, Louis Kauffman, Humberto Maturana, Nelson Vaz, and Ernst von Glasersfeld. In reworking the papers for this book, I have surely done violence to their initial style and intention. I am deeply grateful to all these collaborators for letting me do so; whatever success I have had in conveying an interesting idea should be shared by them in full. In all cases, at the end of the chapter I have listed the sources explicitly.

To my wife Leonor I owe more than acknowledgment; I owe all that comes from vast, nourishing love.

Principles of Biological Autonomy

PART I

AUTONOMY OF THE LIVING AND ORGANIZATIONAL CLOSURE

So long as ideas of the nature of living things remain vague and ill-defined, it is clearly impossible, as a rule, to distinguish between an adaptation of the organism to the environment and a case of fitness of the environment for life, in the very most general sense. Evidently to answer such questions we must possess clear and precise ideas and definitions of living things. Life must by arbitrary process of logic be changed from the varying thing which it is into an independent variable or an invariant, shorn of many of its most interesting qualities to be sure, but no longer inviting fallacy through our inability to perceive clearly the questions involved.

L. Henderson, *The Fitness of the Environment* (1926)

On dira peut-être que l'hypothèse métaphysique d'une dialectique de la Nature est plus intéressante lorsqu'on s'en sert pour comprendre le passage de la matière inorganique aux corps organisés et l'évolution de la vie sur le globe. C'est vrai. Seulement, je ferai remarquer que cette interprétation *formelle* de la vie et de l'évolution ne restera qu'un rêve pieux tant que les savants n'auront pas les moyens d'utiliser comme hypothèse directrice la notion de totalité et celle de totalisation. Il ne sert à rien de décréter que l'évolution des espèces ou que l'apparition de la vie sont des moments de la "dialectique de la Nature" tant que nous ignorons *comment* la vie est apparue et *comment* les espèces se transforment. Pour l'instant, la biologie, dans le domaine concret de ses recherches, demeure positiviste et analytique. Il se peut qu'une connais-

ance plus profonde de son objet lui donne, par ses contradictions, l'obligation de considérer l'organisme dans sa totalité, c'est-à-dire dialectiquement, et d'envisager tous les faits biologiques dans leur relation d'intériorité. Cela *se peut* mais cela *n'est pas sûr*.

J. P. Sartre, *Critique de la Raison Dialectique* (1960)

Chapter 1

Autonomy and Biological Thinking

1.1 Evolution and the Individual

1.1.1

The description, invention, and manipulation of unities generated through distinctions is at the base of all scientific—and rational—enquiry.

This is no less true of living unities. What is peculiar to them, however, is that in our common experience, living unities assert their individuality, that is, living things appear as *autonomous* unities of bewildering diversity endowed with the capacity to reproduce. In these encounters autonomy appears so obviously an essential feature of living systems that whenever something is observed that seems to have it, the naive approach is to deem it alive. Yet, autonomy, although continuously revealed in the self-asserting capacity of living systems to maintain their identity through the active compensation of deformations, seems so far to be the most elusive of their properties.

Autonomy and diversity, the maintenance of identity and the origin of variation in the mode in which this identity is maintained, are the basic challenges presented by the phenomenology of living systems to which men have for centuries addressed their curiosity about life.

In the search for an understanding of autonomy, classical thought, dominated by Aristotle, created vitalism by endowing living systems with a nonmaterial purposeful driving component that attained expression through the realization of their forms. After Aristotle, and as variations of his fundamental notions, the history of biology records many theories that attempt in one way or another to encompass all the phenomenology of living systems under some peculiar organizing force (Hall, 1968). However, the more biologists looked for the explicit formulation of one

or another of these special organizing forces, the more they were disappointed by finding only what they could find anywhere else in the physical world: molecules, potentials, and blind material interactions governed by aimless physical laws. Thence, under the pressure of unavoidable experience and the definite thrust of cartesian thought, a different outlook emerged, and *mechanicism* gradually gained precedence in the biological world by insisting that the only factors operating in the organization of living systems were physical factors, and that no nonmaterial vital organizing force was necessary. In fact, it seems now apparent that any biological phenomenon, once properly defined, can be described as arising from the interplay of physico-chemical processes whose relations are specified by the context of its definition.

Diversity has been removed as a source of bewilderment in the understanding of the phenomenology of living systems by Darwinian thought and particulate genetics, which have succeeded in providing an explanation for it without resorting to any peculiar directing force. Yet the influence of these notions, through their explanation of evolutionary change, has gone beyond the mere accounting for diversity: It has shifted completely the emphasis in the evaluation of the biological phenomenology from the individual to the species, from the unity to the origin of its parts, from the present organization of living systems to their ancestral determination.

Today the two streams of thought represented by the physico-chemical and the evolutionary explanations are braided together. The molecular analysis seems to allow for the understanding of reproduction and variation; the evolutionary analysis seems to account for how these processes might have come into being. Apparently we are at a point in the history of biology where the basic difficulties have been removed.

1.1.2

Biologists, however, are uncomfortable when they look at the phenomenology of living systems as a whole. Many manifest this discomfort by refusing to say what a living system is.¹ Others attempt to encompass present ideas under comprehensive theories governed by organizing notions, such as information-theoretic principles (e.g., Miller, 1966), that require of the biologists the very understanding that they want to provide.

The ever present question is: *What is common to all living systems that allows us to qualify them as living?* If not a vital force, if not an organizing principle of some kind, then what?

In other words, notwithstanding their diversity, all living systems share

¹ Some interesting examples of this discomfort can be found in the discussions transcribed in the series edited by Waddington (1969–1972), where a number of prominent biologists voiced their opinions on the subject.

a common organization which we implicitly recognize by calling them “living.” There is no clear understanding or formulation of such an organization. In fact, the very question is odd to most biologists—with some notable exceptions²—because the great developments in molecular biology have led to an overemphasis on isolated components, and to a disregard of questions pertaining to what makes the living system a whole, autonomous unity that is alive regardless of whether it reproduces or not. As a result, processes that are history dependent (evolution, ontogenesis) and history independent (individual organizations) have been confused. But these two kinds of process must be kept separate and accounted for in related, but distinct terms. A very good recent example is Monod’s idea of the teleonomic apparatus as a characterization of the living organization (Monod, 1970). The capacity and tendency of the genetic material to reproduce and preserve itself generation after generation through the encoding of molecular species in the DNA is pointed at by Monod as the key to life. This, however, pushes all the properties pertaining to the individual unit as a coherent cooperative whole (the functioning cell, for example) into a single molecular species, the DNA, which now contains some abstract description of the teleogenic project of the cell. Ironically, by pushing this kind of mechanicism to such an extreme, Monod finds himself philosophically close to the vitalists, who insisted on a similar reduction of the “life” characteristics to some component other than the cooperative relations of the cellular unity³ (Maturana, 1977; Berthelemy, 1971). Indeed, teleonomic and evolutionary considerations leave the question of the nature of the organization of the living unity untouched.

1.1.3

Our endeavor is to understand the nature of living organization. However, in this approach we make a starting point of the unitary character of a living system. I maintain that evolutionary thought, through its emphasis on diversity, reproduction, and the species in order to explain the dynamics of change, has obscured the necessity of looking at the autonomous nature of living units for the understanding of biological phenomenology. Also I think that the maintenance of identity and the invariance of defining relations in the living unities are at the base of all possible ontogenic and evolutionary transformation in biological systems,

² The notable exceptions that come to mind are Paul Weiss (in Koestler, 1968), and Conrad Waddington (1969–1972).

³ A remarkable passage in the book says: “*L’ultima ratio* de toutes les structures et performances teleonomiques des êtres vivants est donc enfermé dans les sequences de radicaux des fibres polipeptidiques, ‘embryons’ de ces demons de Maxwell biologiques que sont les proteins globulaires. En un sens très réel c’est à ce niveau d’organisation chimie que git, s’il y a en un, le secret de la vie” (Monod, 1970:110).

and this I intend to explore. Thus, our purpose in this first part of the book is to understand the organization of living systems in relation to their unitary character.

1.2 Molecules and Life

1.2.1

Our approach will be mechanistic: No forces or principles will be adduced which are not found in the physical universe. Yet our problem is the living organization, and therefore our interest will not be in properties of components, but in processes and relations between processes realized through components.

This is to be clearly understood. An explanation is always a reformulation of a phenomenon in such a way that its elements appear operationally connected in its generation. Furthermore, an explanation is always given by us as observers, and it is central to distinguish in it what pertains to the system as constitutive of its phenomenology from what pertains to the needs of our domain of description, and hence to our interactions with it, its components, and the context in which it is observed. Since our descriptive domain arises because we simultaneously behold the unity and its interactions in the domain of observation, notions arising from cognitive and expositional needs in the domain of description do not pertain to the explanatory notions for a constitutive organization of the unity (phenomenon). We shall return to this important issue very often in this book.

Furthermore, an explanation may take different forms according to the nature of the phenomenon explained. Thus, to explain the movement of a falling body one resorts to properties of matter, and to laws that describe the conduct of material bodies according to these properties (kinetic and gravitational laws), while to explain the organization of a control plant one resorts to relations and laws that describe the conduct of relations. In the first case, the materials of the causal paradigm are bodies and their properties; in the second case, they are relations and their relations, independently of the nature of the bodies that satisfy them. In this latter case, in our explanations of the organization of living systems, we shall be dealing with the relations that the actual physical components must satisfy to constitute such a system, not with the identification of these components. It is our *assumption* that there is an organization that is common to all living systems, whichever the nature of their components. Since our subject is this organization, not the particular ways in which it may be realized, we shall not make distinctions between classes or types of living system.

1.2.2

By adopting this philosophy, we are in fact just adopting the basic philosophy that animates cybernetics and systems theory, with the qualifications to these names that were discussed in the Preface. This is, I believe, nothing more and nothing less than the essence of a modern mechanicism. In saying that living systems are “machines” we are pointing to several notions that should be made explicit. First, we imply a nonanimistic view, which it should be unnecessary to discuss any further. Second, we are emphasizing that a living system is defined by its organization, and hence that it can be explained as any organization is explained, that is, in terms of relations, not of component properties. Finally, we are pointing out from the start the dynamism apparent in living systems and which the word “machine” or “system” connotes.⁴

We are asking, then, a fundamental question: Which is the organization of living systems, what kind of machines are they, and how is their phenomenology, including reproduction and evolution, determined by their unitary organization?

Sources

Maturana, H., and F. Varela (1975), *Autopoietic Systems: A Characterization of the Living Organization*, Biological Computer Lab. Rep. 9.4, Univ. of Illinois, Urbana. Reprinted in Maturana and Varela (1979)

Varela, F., H. Maturana, and R. Uribe (1974), Autopoiesis: The Organization of Living Systems, Its Characterization and a Model, *Biosystems* 5:187.

⁴ In this book “machines” and “systems” are used interchangeably. They obviously carry different connotations, but the differences are inessential, for my purpose, except in seeing the relation between the history of biological mechanism and the modern tendency for systemic analysis. Machines *and* systems point to the characterization of a class of unities in terms of their organization.

Chapter 2

Autopoiesis as the Organization of Living Systems

2.1 The Duality Between Organization and Structure

2.1.1

Machines and biology have been, since antiquity, closely related. From the zoological figures present in astronomical simulacra, through renaissance mechanical imitations of animals, through Descartes's airpipe nerves, to present-day discussions on the computer and the brain, runs a continuous thread. In fact, the very name of *mechanism* for an attitude of inquiry throughout the history of biology reveals this at a philosophical level (de Solla Price, 1966; Hall, 1968). More often than not, mechanism is mentioned in opposition to vitalism, as an assertion of the validity of the objectivity principle in biology: there are no purposes in animal nature. Its apparent purposefulness is similar to the purposefulness of machines. Yet, the fact that one picks machines as a set of objects comparable to living systems deserves a closer look. What in machines makes it possible to establish such a connection?

If one is to have an understanding of a given class of machines, it is obviously insufficient to give a list of its parts or to define its purpose as a human artifact. The way to avoid both insufficiencies is to describe the permitted interrelations of the machine components, which define the possible transitions that the machine can undergo. This, on the one hand, goes beyond the mere listing, and on the other, implies the nature of the output that determines the purpose of the machine. Notably, when looking at the components, one sees that not all of their properties have equal importance. If one is to instantiate (construct or implement) a certain machine, then, in choosing the components, one will take into account only those component properties that satisfy the desired interrelations

leading to the expected sequence of transitions that constitutes the machine description. This is tantamount to saying that the components may be any components at all *as long as their possible interrelations satisfy a given set of desired conditions*. Alternatively, one can say that what specifies a machine is the set of component's interrelations, regardless of the components themselves.

The *relations* that define a machine as a unity, and determine the dynamics of interactions and transformations it may undergo as such a unity, we call the *organization* of the machine. The actual relations that hold between the components that integrate a concrete machine in a given space constitute its *structure*.¹ The organization of a machine (or system) does not specify the properties of the components that realize the machine as a concrete system; it only specifies the relations that these must generate to constitute the machine or system as a unity. Therefore, the organization of a machine is independent of the properties of its components, which are arbitrary, and a given machine can be realized in many different ways by many different kinds of components. In other words, although a given machine can be realized by many different structures, for it to constitute a concrete entity in a given space its actual components must be defined in that space, and have properties that allow them to generate the relations that define it.

We are thus saying that what defines a machine organization is relations, and hence that the organization of a machine has no connection with materiality, that is, with the properties of the components that define them as physical entities. In the organization of a machine, materiality is implied but does not enter *per se*. A Turing machine, for example, is a certain organization; there seems to be a hopeless gap between the way in which a Turing machine is defined and any possible instance (electrical, mechanical, etc.) of it. This has been pointed out by workers in the field of cybernetics. As Ashby puts it:

The truths of cybernetics are not conditional on their being derived from systems and some other branch of science [They] depend in no essential way on the laws of physics or on the properties of matter The materiality is irrelevant, and so is the holding or not of the ordinary laws of physics. (Ashby, 1956:1)

Wiener was pointing to this when he emphasized the primacy of 'information,' not matter or energy. No materialism which does not admit this [distinction], can survive at the present day'' (1961:132).

There are several other situations where a similar disjunction between

¹ It is very unfortunate that in the cybernetics and systems literature, these two terms are used in very many different ways. For example, in Klir's terminology, structure is closer to what I call here organization (Klir, 1969). The present usage, however, does not seem to depart very radically from that of most authors. See Maturana (1975).

materiality and organization appears. Take, for instance, symmetry. One clearly has empirical examples of symmetry. Yet, one can formulate a theory of it in which materiality concepts do not enter at all. Still, it is possible to transport this theory with no modification to a different context where materiality does appear, as in particle physics. Certainly several other examples exist.

2.1.2

The objection might arise that the notion of organization belongs to a more inclusive field, that of mathematics. This objection, however, carries no weight, because the explanatory value of the notions under discussion correlate with empirical circumstances, artificial or natural, that embody them. Thus, there is the symmetry of natural objects and there is the mathematics of symmetry. Similarly, there is the experience of magnetism and there is the mathematics of magnetism. They do not superimpose, but one embodies the other. From this point of view there is no difference between physics and, say, cybernetics. What makes physics peculiar is the fact that the materiality *per se* is implied; thus, the structures described embody concepts that are derived from materiality itself, and do not make sense without it. Despite any advances, in physics one is looking at the structure of materiality. Whether these basic structures are subsumed in such constructs as self-fields is of no import to our argument.

Furthermore, there are no differences in the explanatory paradigm used in the formulation of, say, atomic theory or control theory. In both cases we are dealing with an attempt to reformulate a given phenomenology in such terms that its components are causally connected. Yet in one case the notions are directly related with materiality, while in the other case materiality does not enter at all.

We thus believe that the classical distinction between synthetic and analytic *should be refined*. Within the synthetic one should distinguish two levels: the *materially* synthetic (i.e., where materiality enters *per se* into consideration), and the *nonmaterially* synthetic (i.e., where materiality is implied but is, as such, irrelevant).

In this light, one should look closely at the consequences of the basic assertion for biological mechanism: Living systems are machines of one or several well-defined classes. This is to say: The definitory element of living unities is a certain organization (the set of interrelations leading to a given form of transitions) independent of the structure, the materiality that embodies it; not the nature of the components, but their interrelations. There are three main consequences of this assertion:

1. Any explanation of a biological system must contain at least *two complementary* aspects, one referring to it as an organization, and the

other referring to it as a structure, as an instance. The first must account for the specific (dynamic) configuration of components that define it; the second must account for how its particular components enter into the given interrelations that constitute it.

2. Any biological system *can* be treated in terms of the properties of its actual components as a physical system. There is no limitation whatsoever on doing so, except for the number of variables that one might have to consider. But this is only a problem in computation. Eventually, one should be able to have a physical description as accurate as needed of any biological system. Although such an analysis is insufficient, it is necessary in order to point to the specific structure(s) of biological systems, so that it will be possible to make sense of a given form of interrelations.
3. Insofar as the physical analysis of biological systems is still physics, what is *specific* to biology is precisely the analysis of the class of machines that living systems are, and the changes that these undergo in time. Thus, the specific aspects of any biological explanation belong to the second level outlined above, and are necessarily not deducible from physics. In this sense, biology is not reducible to physics (although the explanatory paradigm is the same, as noted above). Reduction is used here to mean a program which would make it eventually possible to derive biology from physical chemistry, in order to produce a unified science (Shaffer, 1968; Roll, 1970).

Thus, in this complementary organization/structure we find the first important dimension in which the descriptions of a system reflect back our own descriptive maneuvers. It is clear that the need to include both the organization and the structure of a machine for a complete explanation depends entirely on what we, as a community of observers, consider adequate. Such dualities in descriptions are a running theme throughout this book (cf. Part II).

2.1.3

The *use* to which a machine can be put by man is not a feature of the organization of the machine, but of the domain in which the machine operates, and belongs to our description of the machine in a context wider than the machine itself. This is a significant notion. Man-made machines are all made with some purpose, practical or not—some aim (even if it is only to amuse) that is specified. This aim usually appears expressed in the product of the operation of the machine, but not necessarily so. However, we use the notion of purpose when talking of machines because it calls into play the imagination of the listener and reduces the explanatory task in the effort of conveying the organization of a particular machine. In other words, with the notion of purpose we

induce the listener to invent the machine we are talking about. This, however, should not lead us to believe that purposes, or aims, or functions, are to be used as constitutive properties of the machine that we describe with them; such notions belong to the domain of observation, and cannot be used to characterize any particular type of machine organization. The product of the operations of a machine, however, can be used to this end in a nontrivial manner in the domain of descriptions generated by the observer.

This is a very essential instance of the distinction, made before, between notions that are involved in the explanatory paradigm for a system's phenomenology, and notions that enter because of needs of the observer's domain of communication. To maintain a clear record of what pertains to each domain is an important methodological tool, which we use extensively. It seems an almost trivial kind of logical bookkeeping, yet it is too often violated by usage.

2.2 Autopoietic Machines

2.2.1

That living systems are machines cannot be shown by pointing to their components. Rather, one must show their organization in a manner such that the way in which all their peculiar properties arise becomes obvious. In order to do this, we shall first characterize the kind of systems that living systems are, and then show how the peculiar properties of the living may arise as consequences of the organization of this kind of machines.

2.2.2

There are systems that maintain some of their variables constant, or within a limited range of values. This is, in fact, the basic notion of *stability or coherence*, which stands at the very foundation of our understanding of systems (e.g., Wiener, 1961). The way this is expressed in the organization of these machines must be one that defines the process as occurring completely within the boundaries of the machine that the very same organization specifies. Such machines are homeostatic machines, and all feedback is internal to them. If one says that there is a machine M in which there is a feedback loop through the environment, so that the effects of its output affect its input, one is in fact talking about a larger machine M' which includes the environment and the feedback loop in its defining organization.

The idea of autopoiesis capitalizes on the idea of homeostasis, and extends it in two significant directions: first, by making every reference for homeostasis internal to the system itself through mutual interconnec-

tion of processes; and secondly, by positing this interdependence as the very source of the system's identity as a concrete unity which we can distinguish. These are systems that, in a loose sense, produce their own identity: they distinguish themselves from their background. Hence the name autopoietic, from the Greek $\alpha\upsilon\tau\acute{o}\varsigma$ = self, and $\pi\omicron\iota\epsilon\iota\nu$ = to produce.

An autopoietic system is organized (defined as a unity) as a network of processes of production (transformation and destruction) of components that produces the components that: (1) through their interactions and transformations continuously regenerate and realize the network of processes (relations) that produced them; and (2) constitute it (the machine) as a concrete unity in the space in which they exist by specifying the topological domain of its realization as such a network.

It follows that an autopoietic machine continuously generates and specifies its own organization through its operation as a system of production of its own components, and does this in an endless turnover of components under conditions of continuous perturbations and compensation of perturbations. Therefore, an autopoietic machine is a homeostatic (or rather a relations-static) system that has its own organization (defining network of relations) as the fundamental invariant. This is to be clearly understood. Every unity has an organization specifiable in terms of static or dynamic relations between elements, processes, or both. Among these possible cases, autopoietic machines are unities whose organization is defined by a particular network of processes (relations) of production of components, the autopoietic network, not by the components themselves or their static relations. Since the relations of production of components are given only as processes, if the processes stop the relations of production vanish; as a result, for a machine to be autopoietic, its defining relations of production must be continuously regenerated by the components which they produce. Furthermore, the network of processes which constitute an autopoietic machine is a unitary system in the space of the components that it produces and that generate the network through their interactions.

It is important to realize that we are not using the term organization in the definition of an autopoietic machine in transcendental sense, pretending that it has an explanatory value of its own. We are using it only to refer to the specific relations that define an autopoietic system. Thus, autopoietic organization simply means processes concatenated in a specific form: a form such that the concatenated processes produce the components that constitute and specify the system as a unity. It is for this reason that we can say that if at any time this organization is actually realized as a concrete system in a given space, then the domain of the deformations that the system can withstand without loss of identity (that is, maintain its organization) is the domain of changes in which it exists as a unity.

2.2.3

The autopoietic network of processes defines a class of system. The boundaries of this class, are, of course, not sharp, and this comes about because of the nature of the approach we have taken. First, we have taken as a starting point the fact that systems arise as a result of our processes of distinction through some favored criteria. Thus, there will be many different ways in which both the system and its components can be classified, and in which its boundary can be specified. A similar statement is true about the notion of production of components. Depending on the domain of discourse we choose, this notion will vary in connotations. In order to remove such ambiguities, we would have to give rather precise definitions of these words, probably through some mathematical formalism. This we shall not do. It would defeat the very purpose of conveying an intuition about the living organization in a clear form. A second reason for eschewing excessive qualifications is that we characterized autopoietic machines in the context of certain specific objects called living systems, and more concretely, living *cells*. Thus we have in mind, and will keep in mind, such systems as our reference point in order to give the appropriate connotations to notions such as productions and boundary. This particular frame of reference *does* make autopoietic systems into a recognizable class. For example, in a man-made machine in the physical space, say a car, there is an organization given in terms of a concatenation of processes, yet these processes are in no sense processes of production of the components which specify the car as a unity, since the components of a car are all produced by other processes, which are independent of the organization of the car and its operation. Machines of this kind are non-autopoietic dynamic systems. In a natural physical unity like a crystal, the spatial relations among the components specify a lattice organization that defines it as a member of a class (a crystal of a particular kind), while the kinds of component that constitute it specify it as a particular case in that class. Thus, the organization of a crystal is specified by the spatial relations that define the relative positions of its components, while these specify its unity in the space in which they exist—the physical space. This is not so with an autopoietic machine. In fact, although we find spatial relations among its components whenever we actually or conceptually freeze it for an observation, the observed spatial relations do not (and cannot) define it as autopoietic. This is so because the spatial relations between the components of an autopoietic machine are specified by the network of processes of production of components that constitute its organization, and they are therefore necessarily in continuous change. A crystal organization, then, lies in a different domain than the autopoietic organization: a domain of relations between components, not of relations between processes of production of components; a domain of processes, not of con-

catenations of processes. We normally acknowledge this by saying that crystals are static.

Whether one can classify as autopoietic other systems (such as social or physical) is, of course, dependent on whether one can give a precise connotation to the idea of component production processes and the generation of a boundary in some appropriate space where the components exist, and yet not violate the usage of words, such as production, so as to render them meaningless. I will return to this point later in the book, but it is fair to anticipate my view in saying that I see autopoiesis as *one* possible form of autonomy (or organizational closure, as defined later), and that this term should be restricted to systems, whether natural or artificial, that are characterized by a network that is, or resembles very closely, a chemical network.

2.2.4

The consequences of the autopoietic organization are paramount:

1. Autopoietic machines are autonomous; that is, they subordinate all changes to the maintenance of their own organization, independently of how profoundly they may otherwise be transformed in the process. Other machines, henceforth called *allopoeitic* machines, have as the product of their functioning something different from themselves (as in the car example). Since the changes that allopoeitic machines may suffer without losing their definitory organization are necessarily subordinated to the production of something different from themselves, they are not autonomous.
2. Autopoietic machines have individuality; that is, by keeping their organization as an invariant through its continuous production, they actively maintain an identity that is independent and yet makes possible their interactions with an observer. Allopoeitic machines have an identity that depends on the observer and is not determined through their operation, because its product is different from themselves; allopoeitic machines do have an externally defined individuality.
3. Autopoietic machines are unities because, and only because, of their specific autopoietic organization: Their operations specify their own boundaries in the processes of self-production. This is not the case with an allopoeitic machine, whose boundaries are defined completely by the observer, who, by specifying its input and output surfaces, specifies what pertains to it in its operations.
4. Autopoietic machines do not have inputs or outputs. They can be perturbed by independent events and undergo internal structural changes which compensate these perturbations. If the perturbations are repeated, the machine may undergo repeated series of internal changes, which may or may not be identical. Whichever series of

internal changes takes place, however, they are always subordinated to the maintenance of the machine organization, a condition which is definitive for the autopoietic machines. Thus if there is a relation between these changes and the course of perturbations to which we may point, it pertains to the domain in which the machine is observed, but not to its organization. Although an autopoietic machine can be treated as an allopoietic machine, this treatment does not reveal its organization as an autopoietic machine. In fact, autopoietic and allopoietic descriptions of a system are complementary pairs, depending on the observer's needs. They are a particular instance of what, later on, we characterize as the universal duality between autonomous and control descriptions (cf. Part II).

2.2.5

The actual way in which an organization such as the autopoietic organization may in fact be implemented in the physical space—that is, the physical structure of the machine—varies according to the nature (properties) of the physical materials which embody it. Therefore there may be many different kinds of autopoietic machines in the physical space (physical autopoietic machines); all of them, however, will be organized in such a manner that any physical interference with their operation outside their domain of compensations will result in their disintegration, that is, in the loss of autopoiesis. It also follows that the actual way in which the autopoietic organization is realized in one of these machines (its structure) determines the particular perturbations it can suffer without disintegration, and hence the domain of interactions in which it can be observed. These features of the actual concreteness of autopoietic machines embodied in physical systems allow us to talk about particular cases, to put them in our domain of manipulation and description, and hence to observe them in the context of a domain of interactions that is external to their organization. This has two kinds of fundamental consequence:

1. We can describe physical autopoietic machines, and also manipulate them, as parts of a larger system that defines the independent events which perturb them. Thus, as noted above, we can view these perturbing independent events as inputs, and the changes of the machine that compensate these perturbations as outputs. To do this, however, amounts to treating an autopoietic machine as an allopoietic one, and we thereby recognize that if the independent perturbing events are regular in their nature and occurrence, an autopoietic machine can in fact be integrated into a larger system as a component allopoietic machine, without any alteration in its autopoietic organization.
2. We can analyze a physical autopoietic machine in its physical parts,

and treat all its partial homeostatic and regulatory mechanisms as allopoietic machines (submachines) by defining their input and output surfaces. Accordingly then, these submachines are necessarily components of an autopoietic machine and are defined by relations which they satisfy in determining its organization. The fact that we can divide physical autopoietic machines into parts does not reveal the nature of the domain of interactions that they define as concrete entities operating in the physical universe.

2.3 Living Systems

2.3.1

If living systems are machines, that they are physical autopoietic machines is trivially obvious; they transform matter into themselves in a manner such that the product of their operation is their own organization. However, we deem the converse as also true: A physical system, if autopoietic, is living. In other words, we claim that the notion of *autopoiesis is necessary and sufficient to characterize the organization of living systems*. This proposed equivalence raises, of course, quite a number of philosophical arguments with a long-standing history in the philosophy of biology. It seems useful to comment very briefly on three of them:

1. Machines and systems are generally viewed as natural or human-made artifacts with completely known properties that make them, at least conceptually, perfectly predictable. Contrariwise, living systems are *a priori* frequently viewed as ultimately unpredictable systems, with purposeful behavior similar to ours. If living systems were machines, they could be made by man and, according to the view mentioned above, it seems unbelievable that man could manufacture a living system. This view can be easily disqualified, because it either implies the belief that living systems cannot be understood because they are too complex for our meager intellect and will remain so, or that the principles that generate them are intrinsically unknowable; either implication would have to be accepted *a priori* without proper demonstration. There seems to be an intimate fear that the awe of life and the living would disappear if a living system could be not only reproduced, but designed by man. This is nonsense; the beauty of life is not a consequence of its inaccessibility to our understanding.
2. To the extent that the nature of the living organization is unknown, it is not possible to recognize when one has at hand, either as a concrete synthetic system or as a description, a system that exhibits it. Unless one knows which is the living organization, one cannot know which organizations are alive. In practice, it is accepted that plants and

animals are living, but they are characterized as living through the enumeration of certain properties. Among these, reproduction and evolution appear as determinant, and for many observers the condition of living appears subordinated to the possession of these properties. However, when these properties are incorporated in a concrete or conceptual man-made system, those who do not accept emotionally that the nature of life can be understood immediately apprehend other properties as relevant, and manage to refrain from accepting any synthetic system as living by continually specifying new requirements.

3. It is very often assumed that observation and experimentation are alone sufficient to reveal the nature of living systems, and no theoretical analysis is expected to be necessary, still less sufficient, for a characterization of the living organization. It would take too long to state why we depart from this radical empiricism. Epistemological and historical arguments more than justify the contrary view: Every experimentation and observation implies a theoretical perspective, and no experimentation or observation has significance or can be interpreted outside the theoretical framework in which it took place.

2.3.2

Our endeavor has been to put forth a characterization of living systems, such that all their phenomenology could be understood through it. We have tried to do this by pointing at autopoiesis in the physical space as a necessary and sufficient condition for a system to be a living one.

To know that a given aim has been attained is not always easy. In the case at hand, the only possible indication that we have attained our aim is the reader's agreement that all the phenomenology of living systems is illuminated by this view, and that reproduction and evolution indeed require and depend on autopoiesis. The following pages are devoted to this thesis.

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Chapter 3

A Tesselation Example of Autopoiesis

3.1 The Model

3.1.1

To make the foregoing a bit less abstract, I wish to present at this point a simple model that displays the autopoietic organization. This model is presented in an imaginary, two-dimensional space of components, in the manner of tessellation automata (Burks, 1970). As will be obvious, the model is inspired in the kind of chemical productions existing in a living cell; in fact, the model can be taken as a simplification of such productions.

This model is significant in two respects: On the one hand, it permits the observation of the autopoietic organization at work in a system simpler than any known living system, as well as its spontaneous generation from components; on the other hand, it may permit the development of formal tools for the analysis and synthesis of autopoietic systems.

3.1.2

The model consists of a two-dimensional universe where numerous elements \circ ("substrates") and a few $*$ ("catalysts") move randomly in the spaces of a quadratic grid. These elements are endowed with specific properties that determine interactions that may result in the production of other elements \square ("links") having properties of their own, including the capability of interactions ("bonding"). Let the interactions and transformations be as follows:

Composition: $* + 2\circ \rightarrow * + \square$ (3.1)

Concatenation: $\underbrace{\square - \square - \dots - \square}_n + \square \rightarrow \underbrace{\square - \square - \dots - \square}_{n+1}$,
 $n = 1, 2, 3, \dots$ (3.2)

Disintegration: $\square \rightarrow 2\circ$. (3.3)

The interaction (3.1) between the catalyst $*$ and two substrate elements $2\circ$ is responsible for the composition of an unbonded link \square . These links may be bonded through the interaction (3.2), which concatenates these bonded links to unbranched chains of \square 's. A chain so produced may close upon itself, forming an enclosure which we assume to be penetrable by the \square 's, but not by $*$. Disintegration, (3.3), is assumed to be independent of the state of links \square , i.e., whether they are free or bound, and can be viewed either as a spontaneous decay or as a result of a collision with a substrate element.

In order to visualize the dynamics of the system, we show two sequences (Figures 3-1 and 3-2) of successive stages of transformation as they were obtained from the printout of a computer simulation of this system.¹

If an \square -chain closes on itself enclosing an element $*$ (Figure 3-1), the \square 's produced within the enclosure by the interaction (3.1) can replace in the chain, via (3.2), the elements \square that decay as a result of (3.3) (Figure 3-2). In this manner, a unity is produced, which constitutes a network of productions of components that generate and participate in the network of productions that produced these components by effectively realizing the network as a distinguishable entity in the universe where the elements exist. Within this universe these systems satisfy the autopoietic organization. In fact, the element $*$ and elements \circ produce elements \square in an enclosure formed by a two-dimensional chain of \square 's; as a result the \square 's produced in the enclosure replace the decaying \square 's of the boundary, so that the enclosure remains closed for $*$ under continuous turnover of elements, and under recursive generation of the network of productions, which thus remains invariant (Figure 3-1 and 3-2). This unity cannot be described in geometric terms, because it is not defined by the spatial relations of its components. If one stops all the processes of the system at a moment at which $*$ is enclosed by the \square -chain, so that spatial relations between the components become fixed, one indeed has a system definable in terms of spatial relations, that is, a crystal, but not an autopoietic unity.

3.2 Interpretations

3.2.1

It should be apparent from this model that the processes generated by the properties of the components [(3.1)–(3.3)] can be concatenated in a number of ways. The autopoietic organization is but one of them, yet it

¹ Details of the computation are given in Appendix A. To facilitate appreciation of the developments of the model, Figures 3-1 and 3-2 are drawn from computer printout, changing the symbols actually used in the computations.

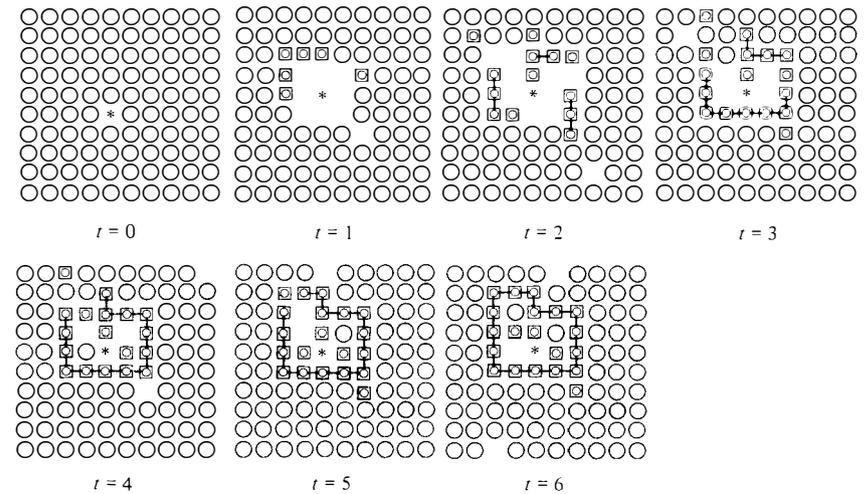


Figure 3-1.

The first seven instants ($0 \rightarrow 6$) of one computer run, showing the spontaneous emergence of a unit in this two-dimensional domain. Interactions between substrate \circ and catalyst $*$ produce chains of bonded links \square which eventually enclose the catalyst, thus closing a network of interactions, which constitutes an autopoietic unity in this domain.

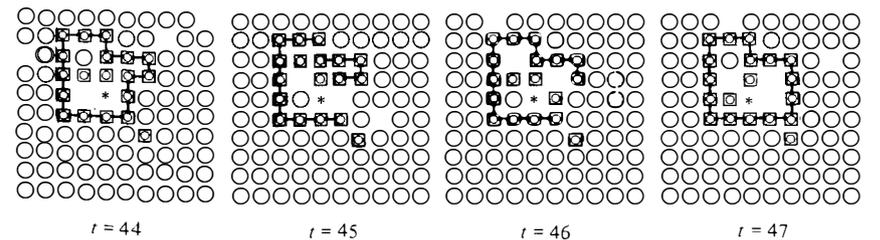
From Varela et al. (1974).

is the one that, by definition, implies the realization of a dynamic unity. The same components can generate other, allopoietic organizations; for example, a chain which is defined as a sequence of \square 's is clearly allopoietic, since the production of the components that realize it as a unity does not enter into its definition as a unity. Thus, the autopoietic orga-

Figure 3-2.

Four successive instants ($44 \rightarrow 47$) in the same computer run of Figure 3-1, showing regeneration of the boundary broken by spontaneous decay of links. Ongoing production of links reestablishes the unity's border under changes of form and turnover of components.

From Varela et al. (1974).



nization is neither represented nor embodied in (3.1)–(3.3), as in general no organization is represented or embodied in the properties that realize it.

In the case described, as in a broad spectrum of other studies that can generically be called tessellation automata (von Neumann, 1966; Burks, 1970), the starting point is a generalization of the physical situation. In fact, one defines a space where spatially distinguishable components interact, thus embodying the concatenation of processes which lead to events among the components. This is of course what happens in the molecular domain, where autopoiesis as we know it takes place. For the purpose of explaining and studying the notion of autopoiesis, however, one may take a more general view, as we have done here, and revert to the tessellation domain, where physical space is replaced by any space (a two-dimensional one in the model), and molecules by entities endowed with some properties. The phenomenology is unchanged in all cases: the autonomous self-maintenance of a unity while its organization remains invariant in time.

It is apparent that in order to have autopoietic systems, the components cannot be simple in their properties. In the present case we required that the components have specificity of interactions, forms of linkage, mobility, and decay. None of these properties are dispensable for the formation of this autopoietic system. The necessary feature is the presence of a boundary that is produced by a dynamics such that the boundary creates the conditions required for this dynamics.

3.2.2

It is interesting to note that, though inspired by the idea of autopoiesis, this tessellation automaton is of some independent interest (see also Zeleny and Pierre, 1976; Zeleny, 1977). It is fundamentally distinct from other tessellation models, such as Conway's well-known game of "life" (Gardner, 1971) and the other lucid games proposed by Eigen and Winkler (1976), because in these models the essential property studied is that of reproduction and evolution, and not that of individual self-maintenance. In other words, the process by which a unity maintains itself is fundamentally different from the process by which it can duplicate itself in some form or another. Production does not entail reproduction, but reproduction does entail some form of self-maintenance or identity. In the case of von Neumann, Conway, and Eigen, the question of the identity or self-maintenance of the unities they observe in the process of reproducing and evolving is left aside and taken for granted; it is not the question these authors are asking at all.

How easily an autopoietic model like the one presented above could be generalized to three dimensions is an open question. There seem to be no conceptual difficulty involved. However, it is my suspicion that

one further dimension will require a significant increase in complexity of the properties in the components, and the simplicity of the rules embodied in (3.1)–(3.3) will be lost. One further study that would be worth some attention is how much more complexity in the rules of interactions would be required for this simple two-dimensional model to reproduce itself, thus bringing it closer to the studies of von Neumann and Eigen mentioned above. This study seems particularly important in the light of difficult problem posed by the combination between self-maintenance and reproduction, which requires some combination of purely dynamic processes of production and (discrete) processes of specification of components (e.g. Eigen, 1971; Pattee, 1977).

Another interesting point about this tessellation model is that the properties of the components that are minimally required to produce the autopoietic dynamic could be illuminating for the kind of properties required in the molecular domain. Thus, these kinds of studies potentially hold a key both for the synthesis of molecular autopoietic units, and for the understanding of neobiogenesis. We believe that the synthesis of molecular autopoiesis can be attempted at present, as suggested by studies like those on microspheres and liposomes (Fox, 1965; Bangham, 1968) when analyzed in the present framework. Consider, for example, a liposome whose membrane lipidic components are produced and/or modified by reactions among its components that take place only under the conditions of concentration produced within the liposome membrane. Such a liposome would constitute an autopoietic system. Experiments along these lines are only beginning (Guiloff, 1978).

Source

Varela, F., H. Maturana, and R. Uribe (1974), Autopoiesis: the organization of living systems, its characterization and a model, *Biosystems* 5:187.

Chapter 4

Embodiments of Autopoiesis

4.1 Autopoietic Dynamics

4.1.1

That a cell is an autopoietic system is apparent in its life cycle. What is not obvious is how the cell is a molecular embodiment of autopoiesis, as should be apparent from its analysis in terms of what we may call the “dimensions” of its autopoietic dynamics.

1. *Production of Constitutive Relations.* Constitutive relations are relations that determine the topology of the autopoietic organization, and hence its physical boundaries. The production of constitutive relations through the production of the components that hold these relations is one of the defining dimensions of an autopoietic system. In the cell such constitutive relations are established through the production of molecules (proteins, lipids, carbohydrates, and nucleic acids) that determine the topology of the relations of production in general, that is, molecules that determine the relations of physical neighborhood necessary for the components to hold the relations that define them. The cell defines its physical boundaries through the production of constitutive relations that specify its topology. There is no specification within the cell of what it is not.
2. *Production of Relations of Specifications.* Relations of specifications are relations that determine the identity (properties) of the component of the autopoietic organization, and hence, in the case of the cells, its physical feasibility. The establishment of relations of specification, through the production of components that can hold these relations, is another of the defining dimensions of an autopoietic system. In the

cell such relations of specification are produced mainly through the production of nucleic acids and proteins that determine the identity of the relations of production in general. In the cell this is obviously obtained, on the one hand, by relations of specificity between DNA, RNA, and proteins, and on the other hand, by relations of specificity between enzymes and substrates. Such production of relations of specificity holds only within the topological substrate defined by the production of relations of constitution. There is no production in the cell as an autopoietic system of relations of specification that do not pertain to it.

3. *Production of Relation of Order.* Relations of order are those that determine the dynamics of the autopoietic organization by determining the concatenation of the production of relations of constitution, specification, and order, and hence its actual realization. The establishment of relations or order through the production of components that control the production of relations (of constitution, specification, and order) constitute the third dimension of the autopoietic dynamics. In the cell, relations or order are established mainly by the production of components (metabolites, nucleic acids, and proteins) that control the speed of production of relations of constitution, specification, and order. Relations of order thus make up a network of parallel and sequential relations of constitution, specification, and order that constitute the cell as an invariant dynamic topological unity. There is no ordering through the autopoietic organization of the cell of processes that do not belong to it.

If one examines a cell, it is apparent that DNA participates in the specification of polypeptides, and hence of proteins, enzymatic and structural, which specifically participate in the production of proteins, nucleic acids, lipids, glucides, and metabolites. Metabolites (which include all small molecules, monomers or not, produced in the cell) participate in the regulation of the speed of the various processes and reactions that constitute the cell, establishing a network of interrelated speeds in parallel and sequentially interconnected processes, both by gating and by constitutive participation, in such a way that all reactions are functions of the state of the transforming network that they integrate. All processes occur bound to a topology determined by their participation in the processes of production of constitutive relations.

4.1.2

In current usage, cellular processes are simplified by supposing that specification is mostly effected by nucleic acids, constitution by proteins, and order (regulation) by metabolites. The autopoietic process, however, is closed in the sense that it is entirely specified by itself, and such

simplification represents our cognitive relation with it, but does not operationally reproduce it. In the actual system, specification takes place at all points where its organization determines a specific process (protein synthesis, enzymatic action, selective permeability); ordering takes place at all points where two or more processes meet (changes of speed or sequence, allosteric effects, competitive and noncompetitive inhibition, facilitation, inactivation) determined by the structure of the participating components; constitution occurs at all places where the structure of the components determines physical neighborhood relations (membranes, particles, active sites in enzymes). What makes this system a unity with identity and individuality is that all the relations of production are coordinated in a system describable as having an invariant organization. In such a system any deformation at any place is compensated for, not by bringing the system back to an identical state in its components such as might be described by considering its structure at a given moment, but rather by keeping its *organization* constant as defined by the relation of the productions that constitute autopoiesis. The only thing that defines the cell as a unity (as an individual) is its autopoiesis, and thus, the only restriction put on the existence of the cell is the maintenance of autopoiesis. All the rest (that is, its structure) can vary: Relations of topology, specificity, and order can vary as long as they constitute a network in an autopoietic space.

4.2 Questions of Origin

4.2.1

The production of relations of constitution, specification, and order are not characteristic of autopoietic systems. They are inherent in unitary interactions in general, and in molecular interactions in particular; they depend on the properties of the units or molecules as expressed in the geometric and energetic relationships that they may adopt. Thus, the geometric properties of the molecules determine the relations of constitution—that is, the topology, the physical neighborhoods, or the spatial relations into which they may enter. The chemical properties of the molecules determine their possible interactions, and hence the relations of specificity, which are a dimension independent of the relations of constitution. Together they determine the sequence and concatenation of molecular interactions, that is, relations of order.

Accordingly, autopoiesis may arise in a molecular system if the relations of production are concatenated in such a way that they produce components specifying the system as a unity that exists only while it is actively produced by such concatenation of processes. This is to say that autopoiesis arises in a molecular system only when the relation that concatenates these relations is produced and maintained constant through

the production of the molecular components that constitute the system through this concatenation. Thus, in general, the question of the origin of an autopoietic system is a question about the conditions that must be satisfied for the establishment of an autopoietic dynamics. This problem, then, is not a chemical one, in terms of what molecules took or can take part in the process, but a general one of what relations the molecules or any constitutive units should satisfy.

A clear example of this situation is Eigen's studies on the origin of life (Eigen, 1971, 1973; Eigen and Schuster, 1977), with the successive steps of stability in chemical reactions that could have led to a cell-like system, and in particular, to something like a genetic code. By analytic methods derived from nonequilibrium thermodynamics, combined with computer simulations, Eigen shows how selective pressures could have been brought to bear in the process of molecular evolution. Interestingly enough, he concludes that of central importance to this process is a circular concatenation of processes, such as the hypercycle of Figure 4-1. In this generalized situation, the processes of specification, constitution, and order are related in a typically autopoietic fashion, although Eigen has not put emphasis on boundary generation, since his interest lies in the processes of specification.

4.2.2

The establishment of an autopoietic system cannot be a gradual process: Either a system is an autopoietic system or it is not. In fact, its establishment cannot be gradual because an autopoietic system is defined as a system, that is, it is defined as a topological unity by its organization. Thus, either a topological unity is formed through its autopoietic organization, and the autopoietic system is there and remains, or there is no topological unity, or else a topological unity is formed in a different manner and there is no autopoietic system but there is something else. Accordingly, there are not and cannot be intermediate systems. We can describe a system and talk about it as if it were a system that would, with little transformation, become an autopoietic system, because we can imagine different systems with which we can compare it, but such a system would be intermediate only in our description, and in no organizational sense would it be a transitional system.

In general the problem of the origin of autopoietic systems has two aspects: One refers to their feasibility, and the other to the possibility of their spontaneous occurrence. The first aspect can be stated in the following manner: The establishment of any system depends on the presence of the components that constitute it, and on the kinds of interactions into which they may enter; thus, given the proper components and the proper concatenation of their interactions, the system is realized. The concrete

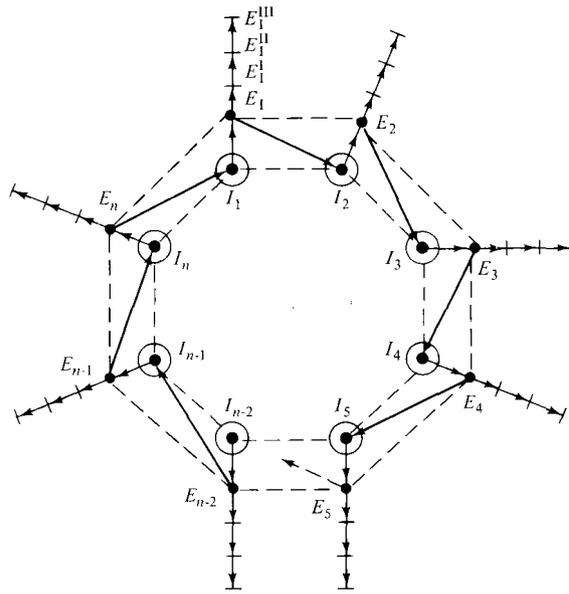


Figure 4-1.

Eigen's self-producing hypercycle. An RNA-like molecule I_i serves as the specification for a catalytic molecule E_i . Each branch from E_i may include several other processes (e.g., polymerization, regulation), but one of these branches provides a coupling to the carrier I_{i+1} . These linkages close, so that E_n enhances the formation of I_1 . The hypercycle, as studied through a system of nonlinear differential equations, is postulated as a unit of selection in the early evolution of life.

After Eigen (1974).

question of the feasibility of a molecular autopoietic system is, then, the question of the conditions in which different chemical processes can be concatenated to form topological unities that constitute relational networks in the autopoietic space. The second aspect can be stated in the following manner: Given the feasibility of autopoietic systems, and given the existence of terrestrial autopoietic systems, there are natural conditions under which these may be spontaneously generated. Concretely the question would be: Which were or are the natural conditions under which the components of the autopoietic systems arose or arise spontaneously on Earth? This question cannot be answered independently of the manner in which the feasibility question is answered, particularly with regard to the feasibility of one or several different kinds of molecular autopoietic systems. The presence today of one mode of autopoietic organization on

Earth (the nucleic-acid-protein system) cannot be taken to imply that the feasibility question has only one answer.

Source

Maturana, H., and F. Varela (1975), *Autopoietic Systems: A Characterization of the Living Organization*, Biological Computer Lab. Rep. 9.4, Univ. of Illinois, Urbana. Reprinted in Maturana and Varela (1979).

Chapter 5

The Individual in Development and Evolution

5.1 Introduction

Living systems embody the living organization. Living systems are autopoietic systems in the physical space. The diversity of living systems is apparent: it is also apparent that this diversity depends on reproduction and evolution. Yet, reproduction and evolution do not enter into the characterization of the living organization as autopoiesis, and living systems are defined as unities by their autopoiesis. This is significant because it makes it evident that the *phenomenology* of living systems depends on their being autopoietic unities. In fact, reproduction requires the existence of a unity to be reproduced, and it is necessarily secondary to the establishment of such a unity; evolution requires reproduction and the possibility of change, through reproduction of that which evolves, and it is necessarily secondary to the establishment of reproduction. It follows that the proper evaluation of the phenomenology of living systems, including reproduction and evolution, requires their proper evaluation as autopoietic unities.

5.2 Subordination to the Condition of Unity

Unity (distinguishability from a background, and hence from other unities) is the sole necessary condition for existence in any given domain. In fact, the nature of a unity and the domain in which it exists are specified by the process of its distinction and determination; this is so regardless of whether that process is conceptual (as when a unity is defined by an observer through an operation of distinction in his domain of discourse and description), or physical (as when an autonomous unity

comes to be established through the actual working of its defining properties that assert its distinction from a background through their actual operation in the physical space). Accordingly, different kinds of unity necessarily differ in the domain in which they are established, and having different domains of existence, they may or may not interact according as these domains do or do not interact.

Unity distinction, then, is not an abstract notion of purely conceptual validity for descriptive or analytical purposes, but is an operative notion referring to the process through which a unity becomes asserted or defined: *the conditions that specify a unity determine its phenomenology*. In living systems, these conditions can be traced to their autopoietic organization. In fact, autopoiesis implies the subordination of all change in the autopoietic system to the maintenance of its autopoietic organization, and since this organization defines the system as a unity, it implies total subordination of the phenomenology of the system to the maintenance of its unity. This subordination has the following consequences:

1. The establishment of a unity defines the domain of its phenomenology, but the way the unity is constituted—its structure—defines the kind of phenomenology that it generates in that domain. It follows that the particular form adopted by the phenomenology of each autopoietic (biological) unity depends on the particular way in which its individual autopoiesis is realized. It also follows that the domain of ontogenic transformations (including conduct) of each individual is the domain of the homeorhetic trajectories through which it can maintain its autopoiesis.
2. All the biological phenomenology is necessarily determined and realized through individuals (that is, through autopoietic unities in the physical space), and consists in all the paths of transformations that they undergo, singly or in groups, in the process of maintaining invariant their individual defining relations. Whether or not in the process of their interactions the autopoietic unities constitute additional unities is irrelevant for the subordination of the biological phenomenology to the maintenance of the identity of the individuals. In fact, if a new unity is produced that is not autopoietic, its phenomenology, which will necessarily depend on its organization, will be biological or not according to its dependence on the autopoiesis of its components, and will accordingly depend or not depend on the maintenance of these as autopoietic units. If the new unity is autopoietic, then its phenomenology is biological and obviously depends on the maintenance of its autopoiesis, which in turn may or may not depend on the autopoiesis of its components.
3. The identity of an autopoietic unity is maintained as long as it remains autopoietic, that is, as long as it, as a unity in the physical space,

remains a unity in the autopoietic space, regardless of how much it may otherwise be transformed in the process of maintaining its autopoiesis.

5.3 Plasticity of Ontogeny: Structural Coupling

Ontogeny is the history of the structural transformation of a unity. Accordingly, the ontogeny of a living system is the history of maintenance of its identity through continuous autopoiesis in the physical space. From the mere fact that a physical autopoietic system is a dynamic system, realized through relations of productions of components that imply concrete physical interactions and transformations, it is a necessary consequence of the autopoietic organization of a living system that its ontogeny should take place in the physical space.

Since the way an autopoietic system maintains its identity depends on its particular way of being autopoietic (that is, on its particular structure), different classes of autopoietic systems have different classes of ontogenies. Moreover, since an autopoietic system does not have inputs or outputs, all the changes that it may undergo without loss of identity, and hence with maintenance of its defining relations, are necessarily determined by its invariant organization. Consequently, the phenomenology of an autopoietic system is necessarily always commensurate with the deformations that it suffers without loss of identity, and with the deforming environment in which it lies; otherwise it would disintegrate.

As a consequence of the invariance of the autopoietic organization, the way the autopoiesis is realized in any given unity may change during its ontogeny, with the sole restriction that this should take place without loss of identity, that is, through uninterrupted autopoiesis. Although the changes that an autopoietic system may undergo without loss of identity while compensating its deformations under interactions are determined by its organization, the sequence of such changes is determined by the sequence of these deformations. There are two sources of deformations for an autopoietic system as they appear to be to an observer: one is constituted by the environment as a source of independent events in the sense that these are not determined by the organization of the system; the other is constituted by the system itself as a source of states that arise from compensations of deformations, but that themselves can constitute deformations that generate further compensatory changes. In the phenomenology of the autopoietic organization these two sources of perturbations are indistinguishable, and in each autopoietic system they braid together to form a single ontogeny. Thus, although in an autopoietic system all changes are internally determined, for an observer its ontogeny partly reflects its history of interactions with an independent environment. Accordingly, two otherwise equivalent autopoietic systems may have different ontogenies.

In summary: *the continued interactions of a structurally plastic system in an environment with recurrent perturbations will produce a continual selection of the system's structure.* This structure will determine, on the one hand, the state of the system and its domain of allowable perturbations, and on the other hand will allow the system to operate in an environment without disintegration. We refer to this process as *structural coupling* (Maturana, 1977). If we can consider the system's environment also as a structurally plastic system, then the system and the environment will have an interlocked history of structural transformations, selecting each other's trajectories.

Thus, we again find the relevance of the position taken by the observer and his cognitive needs. An observer beholding an autopoietic system as a unity in a context that he also observes, and that he describes as its environment, may distinguish in it internally and externally generated perturbations, even though these are intrinsically indistinguishable for the dynamic autopoietic system itself. The observer can use these distinctions to make statements about the structural coupling of the system which he observes, and he can use this history to describe an environment (which he infers) as the domain in which the system exists. He cannot, however, infer from the observed correspondence between the ontogeny of the system and the environment that this ontogeny describes, or from the environment in which he sees it, a constitutive *representation* of these in the organization of the autopoietic systems, for this would only mean a confusion of observational perspectives across a logical type. The continuous correspondence between conduct and environment revealed during ontogeny is the result of the invariant nature of the autopoietic organization, and not of the existence of any representation of the environment in it; nor is it at all necessary that the autopoietic system should "obtain" or develop such a representation to persist in a changing environment. To talk in a meaningful and sophisticated way about a representation of the environment in the organization of a living system may be essential in our explanatory discourse (see Chapter 9), but it is inessential to define what makes a certain system a unit. Informational notions such as representations only become necessary to explain phenomena that unities can exhibit over long spans of time and with a certain degree of reliability. But this is another matter than defining the organization of a unit. We shall return later to this important duality of the observer's perspective.

5.4 Reproduction and the Complications of the Unity

5.4.1

Reproduction requires a unity to be reproduced; this is why reproduction is operationally secondary to the establishment of the unity, and it cannot enter as a defining feature of the organization of living systems. Further-

more, since living systems are characterized by their autopoietic organization, reproduction must necessarily have arisen as a complication of autopoiesis during autopoiesis, and its origin must be viewed and understood as secondary to, and independent of, the origin of the living organization. The dependence of reproduction upon the existence of the unity to be reproduced is not a trivial problem of precedence, but is an operational problem in the origin of the reproduced system and its relations with the reproducing mechanism. In order to understand reproduction and its consequences in autopoietic systems we must briefly analyze the operational nature of this process in relation to autopoiesis.

There are three phenomena that must be distinguished in relation to the notion of reproduction: replication, copying, and self-reproduction.

1. *Replication*. A system that successively generates unities different from itself, but in principle identical to each other, and with an organization that the system determines in that process, is a replicating system. Replication, then, is not different from repetitive production. Any distinction between these processes arises as a matter of description in the emphasis that the observer puts on the origin of the equivalent organization of the successively produced unities, and on the relevance that this equivalence has in a domain different from that in which the repetitive production takes place. Thus, although all molecules are produced by specific molecular and atomic processes that can at least in principle be repeated, only when certain specific kinds of molecules are produced in relation to the cellular activities (proteins and nucleic acids) by certain repeatable molecular concatenations, is their production called replication. Such a denomination, then, makes reference only to the context in which the identity of the successively produced molecules is deemed necessary, not to a unique feature of that particular molecular synthesis.
2. *Copying*. Copying takes place whenever a given object or phenomenon is mapped by means of some procedure upon a different system, so that an isomorphic object or phenomenon is realized in it. In the notion of copying the emphasis is put on the mapping process, regardless of how this is realized, even if the mapping operation is performed by the model unit itself.
3. *Self-Reproduction*. Self-reproduction takes place when a unity produces another one with a similar organization to its own, through a process that is coupled to the process of its own production. It is apparent that only autopoietic systems can have molecular self-reproduction, because only they are realized through a process of self-production (autopoiesis) in the physical space.

For an observer there is reproduction in all these three processes, because he can recognize in each of them a unitary pattern of organization which is embodied in successively generated systems through the three

well-defined mechanisms. The three processes, however, are intrinsically different because their dynamics gives rise to different phenomenologies, which appear particularly distinct if one considers the network of systems generated under conditions in which change is allowed in the process of reproduction of the successively embodied pattern of organization. Thus, in replication and copying the mechanism of reproduction is necessarily external to the pattern reproduced, while in self-reproduction it is necessarily identical to it. Furthermore, only in self-copying and self-reproduction can the reproducing mechanism be affected by changes in the unities produced that embody the pattern reproduced. It should be clear that the historical interconnections established between independent unities through reproduction vary with the mechanism through which reproduction is achieved.

5.4.2

In living systems presently known on Earth, autopoiesis and reproduction are directly coupled, and hence these systems are truly self-reproducing systems. In fact, in them reproduction is a moment in autopoiesis, and the same mechanism that constitutes one constitutes the other. The consequences of such a coupling are paramount: (1) Self-reproduction must take place during autopoiesis; accordingly the network of individuals thus produced is necessarily self-contained in the sense that it does not require for its establishment a mechanism independent of the autopoietic determination of the self-reproducing unities. Such would not be the case if reproduction were attained through external copying or replication. (2) Self-reproduction is a form of autopoiesis; therefore, variation and constancy in each reproductive step are not independent, and both must occur as expressions of autopoiesis. (3) Variation through self-reproduction of the way the autopoiesis is realized can only arise as a modification during autopoiesis of a preexisting functioning autopoietic structure; consequently, variation through self-reproduction can only arise from perturbations that require further complications to maintain autopoiesis invariant. The history of self-reproductively connected autopoietic systems can only be one of continuous complication of the structures of autopoiesis.

Again, let us note that notions such as coding, message, or information are not, strictly speaking, applicable to the phenomenon of self-reproduction; their use in the description of its mechanism constitutes an attempt to represent it on another descriptive level.

5.5 Evolution, a Historical Network

5.5.1

A historical phenomenon is a process of change in which each of the successive states of a changing system arises as a modification of a

previous state in a causal transformation, and not *de novo* as an independent occurrence. The notion of history may either be used to refer to the antecedents of a given phenomenon as the succession of events that gave rise to it, or be used to characterize the given phenomenon as a process. Therefore, since a causal explanation is always given in the present as a reformulation of the phenomenon to be explained in the domain of interactions of its components (or of isomorphic elements), the history of a phenomenon as a description of its antecedents cannot contribute to its explanation, because the antecedents are not components of the phenomenon which they precede or generate. Conversely, if history as a phenomenon is to be explained in the present as a causal network of sequentially concatenated events in which each event is a state of the network that arises as a transformation of the previous state, then it follows that although history cannot contribute to explaining any phenomenon causally, it can permit an observer to account for the origin of a phenomenon as a state in a causal (historical) network. He can do this because he has independent observational (or descriptive) access to the different states of the historical process.

It is in this context that the phenomenology of autopoietic systems must be considered when viewed in reference to evolution. Biological evolution is a historical phenomenon, and as such it must be explained in the present context by its reformulation as a historical network constituted through the causal interactions of coupled or independent biological events. Furthermore, biological events depend on the autopoiesis of living systems; accordingly, our aim here is to understand how evolution is defined as a historical process by the autopoiesis of the biological unities.

5.5.2

If by evolution we refer to what has taken place in the history of transformation of terrestrial living systems, then evolution as a process is the history of change of a pattern of organization embodied in independent unities sequentially generated through reproductive steps, in which the particular defining organization of each unity arises as a modification of the preceding one (or ones), which thus constitutes both its sequential and its historical antecedent. Consequently, evolution requires sequential reproduction and change in each reproductive step. Without sequential reproduction as a reproductive process in which the defining organization of each unity in the sequence constitutes the antecedent for the defining organization of the next one, there is no history; without change in each sequential reproductive step, there is no evolution. In fact, sequential transformations in a unity without change of identity constitute its ontogeny, that is, its individual history if it is an autopoietic unit.

Reproduction by replication or copying of a single unchanging model

implies an intrinsic decoupling between the organization of the unities produced and their producing mechanism. As a consequence, any change in the reproduced pattern of organization embodied in the unities successively produced by replication of copying from a single model, can only reflect the ontogenies of the reproducing systems or the independent ontogenies of the units themselves. The result is that under no circumstances in these nonsequential reproductive cases does a change in the organization of a unity affect the organization of the others yet to be produced, and, independently of whether they are autopoietic or not, they do not constitute a historical network, and no evolution takes place. The collection of unities thus produced constitutes a collection of independent ontogenies. In sequential reproduction, as it occurs in self-reproducing systems that attain reproduction through autopoiesis, or as it occurs in those copying systems in which each new unity produced constitutes the model for the one, the converse is true. In these cases, there are aspects of the defining organization of each unity that determine the organization of the next one by their direct coupling with the reproductive process, which is thus subordinated to the organization of the reproduced unities. Consequently, changes in these aspects of the organization of the unities sequentially generated that occur either during their own ontogeny, or in the process of their generation, necessarily result in the production of a historical network. The unities successively produced unavoidably embody a changing pattern of organization in which each state arises as a modification of the previous one. In general, then, sequential reproduction with the possibility of change in each reproductive step necessarily leads to evolution, and in particular, in autopoietic systems evolution is a consequence of self-reproduction.

5.5.3

Ontogeny and evolution are completely different phenomena, both in their appearance and in their consequences. In ontogeny—the history of transformation of a unity—the identity of the unity, in whatever space it may exist, is never interrupted. In evolution—a process of historical change—there is a succession of identities, generated through sequential reproduction, which constitute a historical network, and that which changes (evolves), namely the pattern of organization of the successively generated units, exists in a different domain than the units that embody it. A collection of successive ontogenies in whose organization an observer can see relations of maintained change, but that have not been generated through sequential reproduction, do not constitute an evolving system, not even if they reflect the continuous transformation (ontogeny) of the system that produced them. It is inadequate to talk about evolution in the history of change of a single unity in whatever space it may exist; unities only have ontogenies. Thus, it is inadequate to talk about the

evolution of the universe, or the chemical evolution of Earth; one should only talk about the ontogeny of the universe or the chemical history of Earth. Also, there is a biological evolution only in that there is sequential reproduction of living systems; if there were non-self-reproducing autopoietic systems before that, their different patterns of organization did not evolve, and there was only the history of their independent ontogenies.

5.5.4

Selection, as a process in a population of unities, is a process of differential realization in a context that specifies the unitary organizations that can be realized. In a population of autopoietic unities selection is a process of differential realization of autopoiesis, and hence, if these are self-reproducing autopoietic unities, of differential self-reproduction. Consequently, if there is sequential reproduction, and the possibility of change in each reproductive step, then selection can make the transformation of the reproducible pattern of organization embodied in each successive unity a recursive function of the domain of interactions which that very same autopoietic unity specifies. If any system that is realized is necessarily adapted in the domain in which it is realized, and adaptation is the condition of possible realization for any system, then evolution takes place only as a process of continued adaptation of the unities that embody the evolving pattern of organization. Accordingly, different evolving systems will differ only in the domain in which they are realized, and hence in which selection takes place, not in whether they are adaptive or not. Thus, evolution in self-reproducing living systems that maintain their identity in the physical space (as long as their invariant autopoietic organization is commensurate with the restrictions of the ambient in which they exist) is necessarily a process of continued adaptation, because only those of them whose autopoiesis can be realized reproduce, regardless of how much the way they are autopoietic may otherwise change in each reproductive step.

5.5.5

A species is the result of the selection process in a population or collection of populations of reproductively interconnected individuals, which are thus nodes in a historical network. These individuals share a genetic pool, that is, a fundamentally equivalent pattern of autopoietic organization under historical transformations. Historically, a species arises when a reproductive network of this kind develops an independent reproductive network as a branch, which, by being an independent historical network (reproductively separated) has an independent history. It is said that what evolves is the species and that the individuals in their historical existence are subordinated to this evolution. In a superficial

descriptive sense this is meaningful, because a particular species as an existing collection of individuals represents continuously the state of a particular historical network in its process of becoming a species; and if described as a state of a historical network, a species necessarily appears in a process of transformation. Yet the species exists as a unit only in the historical domain, while the individuals that constitute the nodes of this historical network exist in the physical space. Strictly, a historical network is defined by each and every one of the individuals that constitute its nodes, but it is at any moment represented historically by the species as the collection of all the simultaneously existing nodes of the network; in fact, then, a species does not evolve, because as a unity in the historical domain it only has a history of change. What evolves is a pattern of autopoietic organization embodied in many particular variations in a collection of transitory individuals that together define a reproductive historical network. Thus, the individuals, though transitory, are essential, not dispensable, because they constitute a necessary condition for the existence of this historical network that they define. The species is a descriptive notion that represents a historical phenomenon; it does not constitute a *causal* component in the phenomenology of evolution.

5.5.6

It cannot be too strongly emphasized that for evolution to take place as an actual history of change of a pattern of organization through its embodiment in successively generated unities, reproduction must allow for change in the sequentially reproduced organization. In present living systems reproduction takes place as a modification of autopoiesis and is bound to it. This is to be expected. Originally many kinds of autopoietic unities were probably formed, which would mutually compete for the precursors. If any class of them had any possibility of self-reproduction, it is evident that it would immediately displace through selection the other, nonreproducing forms. The onset of the history of self-reproduction need not have been complex; for example, in a system with distributed autopoiesis mechanical fragmentation is a form of self-reproduction. Evolution through selection would appear, with the enhancement of those features of the autopoietic unities that facilitated their fragmentation (and hence the regularity and frequency of self-reproduction) to the extent of making it independent of external accidental forces.

It is at this point that we can see the difference between borderline cases of autopoietic units (such as the model structures discussed in Chapter 3) and the chemical networks operative in cellular systems. Simple chemical structures, as we know them, have no form of reliable but flexible reproduction, and thus are evolutionarily uninteresting, even if they qualify as autopoietic systems. In contrast, the phenomenology that cellular systems can generate is immense. One outstanding question

in this respect is whether there is actually any way of realizing an autopoietic system with an interesting evolutionary phenomenology except through the components which constitute present living cells. But this need not concern us here.

In brief then, once the simplest self-reproducing process takes place in an autopoietic system, evolution is on its course and self-reproduction can enter a history of change, with the ensuing total displacement of any coexisting non-self-reproducing autopoietic unities. *Hence the linkage between autopoiesis and self-reproduction in terrestrial living systems.* Of course it is not possible to say now what actually took place in the origin of biological evolution. The fact is that in present-day living systems self-reproduction is crucially associated with nucleic acids and their role in protein specification. It seems that this could not have been so if the nucleic-acid-protein association were not a condition virtually constitutive of the original autopoietic process, which was secondarily associated with reproduction and variation, as suggested by the studies of Eigen (1971) and Eigen and Schuster (1977) (Figure 4.1).

Source

Maturana, H., and F. Varela (1975), *Autopoietic Systems: A Characterization of the Living Organization*, Biological Computer Lab. Rep. 9.4, Univ. of Illinois, Urbana. Reprinted in Maturana and Varela (1979).

Chapter 6

On the Consequences of Autopoiesis

6.1 Introduction

Autopoiesis in the physical space is necessary and sufficient to characterize a system as a living system. Reproduction and evolution as they occur in the known living systems, and all the phenomena derived from them, arise as secondary processes subordinated to their existence and operation as autopoietic unities. Hence, the biological phenomenology is founded in the phenomenology of autopoietic systems in the physical space. For a phenomenon to be a biological phenomenon it is necessary that it depend in one way or another on the autopoiesis of one or more physical autopoietic unities. This has been the argument so far. Let us now follow some of its implications.

6.2 Biological Implications

6.2.1

We first consider autopoiesis in the physical space. A living system is a living system because it is an autopoietic system in the physical space, and it is a unity in the physical space because of its autopoiesis as a mechanism of identity. Accordingly, any structural transformation that a living system may undergo in maintaining its identity must take place in a manner determined by, and subordinated to, its defining autopoiesis; hence, in a living system loss of autopoiesis is disintegration as a unity and loss of identity—that is, death.

The physical space is defined by components that can be determined by operations that characterize them in terms of properties such as masses, forces, accelerations, distances, fields, etc. Furthermore, such

properties themselves are defined by the interactions of the components that they characterize. In the physical space thus understood, two essential kinds of phenomenology can take place according to the way the components participate in their generation, namely, statical and mechanical (dynamic, machinelike). The statical phenomenology is a phenomenology of relations between *properties* of components; the mechanical phenomenology is a phenomenology of relations between *processes* realized through the properties of components.

What about the biological phenomenology of individual living systems? That is, what about the phenomenology of autopoietic systems that takes place in the physical space? Since a living system is defined as a system by the concatenation of processes of production of components that generate the processes that produce them and constitute the system as a unity in the physical space, biological phenomena are necessarily phenomena of relations between processes that satisfy the autopoiesis of the participant living systems. Accordingly, under no circumstances is a biological phenomenon defined by the properties of its component elements; it is always defined and constituted by a concatenation of processes in relations subordinated to the autopoiesis of at least one living system. For example, the accidental collision of two running animals, as a bodily encounter of living systems, is not a biological phenomenon (even though it may have biological consequences), but the bodily contact of two animals in courtship is.

Strictly, then, although biological and statical phenomena are physical phenomena because they are realized through the properties of their physical components, they differ because statical phenomena are phenomena of relations between properties of components (as previously defined), while biological phenomena are phenomena of relations between processes. Therefore, biological phenomena, as phenomena of relations between processes, are a subclass of the mechanical phenomena that constitute them, and they are defined through the participation of these processes in the realization of at least one autopoietic system. The phenomenology of living systems, then, is the mechanical phenomenology of physical autopoietic machines.

6.2.2

We now arrive at the duality of organization and structure. As the mechanical phenomenology of physical autopoietic machines, the biological phenomenology is perfectly well defined and, in principle, amenable to theoretical treatment through the theory of autopoiesis. It follows that such a theory, as a formal theory, will be a theory of the concatenation of processes of production that constitute autopoietic systems, and not a theory of properties of components of living systems. This says nothing, however, of the difficulties of such a formal theory. In fact, it is apparent

that we are at a stage where analytical tools for the understanding of cooperative, parallel processes are meager, as is dramatically shown in the work of Goodwin (1970, 1976), based on dynamical system modeling. These difficulties, however, may be more theoretical than practical, in view of the possibility of complementary modes of description for systems, and in particular for autopoietic systems, which we discuss later on in Part II.

It also follows that a theoretical biology would be possible only as a theory of the biological phenomenology, and not as the application of physical or chemical notions, which pertain to a different phenomenological domain, to the analysis of the biological phenomena. In fact, it should be apparent now that any attempt to explain a biological phenomenon in statical or non-autopoietic mechanical terms would be an attempt to reformulate it in terms of relations between properties of components, or relations between processes that do not produce a unity in the physical space, and hence would necessarily fail. Since a biological phenomenon takes place through the operation of components, it is always possible to abstract from it component processes that can be adequately described in statical or non-autopoietic mechanical terms, because as abstracted processes they in fact correspond to statical or allopoeitic mechanical phenomena. In such a case, any connection between the statical or non-autopoietic mechanical processes and the biological phenomenon from which the observer abstracts them is provided by the observer who considers both simultaneously, as we often need to do.

This is, in other words, the *duality* between *organizational and structural descriptions*. We seem to be unable to characterize a class or organization unless there is some way of relating such relations in some particular structure. Conversely, no specific structure can serve to account for the phenomenology it generates, unless characterized in terms of the class of organization to which it belongs. Thus we need to preserve the relation between organization and structure of a system, but at the same time not to confuse the two kinds of description, as, apparently, it is easy to do.

The biological phenomenon proper, however, is not and cannot be captured by purely structural explanations, which necessarily remain a reformulation of a phenomenon in a non-autopoietical phenomenological domain. A biological explanation must be a reformulation in terms of processes subordinated to autopoiesis.

6.2.3

An adequate theory of the biological phenomena should permit the analysis of the dynamics of the concrete components of a system in order to determine whether or not they participate in processes that integrate a

biological phenomenon. In fact, no matter how much we think we understand biological problems today, it is apparent that without an adequate theory of autopoiesis it will not be possible to answer questions such as: given a dynamic system, what relations should I observe between its concrete components to determine whether or not they participate in processes that make it a living system? or: given a set of components with well-defined properties, in what processes of production can they participate so that the components can be concatenated to form an autopoietic system? The answer to these questions is essential if one wants to solve the problem of the origin of living systems on Earth. The same question must be answered if one wants to design a living system. In particular, it should be possible to determine from theoretical biological considerations which relations should be satisfied by any set of components if these are to participate in processes that constitute an autopoietic unity. Whether or not one may want to make an autopoietic system is, of course, an ethical problem. However, if our characterization of living systems is adequate, it is apparent that they could be made at will. What remains to be seen is whether such a system has already been made by man although unwittingly, and if so, with what consequences.

Finally, the characterization of living systems as physical autopoietic systems must be understood as having universal value, that is, autopoiesis in the physical space must be viewed as defining living systems anywhere in the universe, however different they may otherwise be from terrestrial ones. This is not to be considered as a limitation of our imagination, nor as a denial that there might exist still unimagined complex systems. It is a statement about the nature of the biological phenomenology: The biological phenomenology is neither more nor less than the phenomenology of autopoietic systems in the physical space.

6.3 Epistemological Consequences

6.3.1

The basic epistemological question in the domain of the biological problems is that which refers to the validity of the statements made about biological systems. It is now obvious that scientific statements made about the universe acquire their validity through their operative effectiveness in their application in their purported domain. Yet any observation, even one that permits us to recognize the operational validity of a scientific statement, implies an epistemology: a body of explicit or implicit conceptual notions that determines the perspective of the observations and, hence, what can and what cannot be observed, what can and what cannot be validated by its operative effectiveness, and what can and what cannot be explained by a given body of theoretical concepts.

This has been a fundamental problem in the conceptual and experimental handling of the biological phenomena, as is apparent in the history of biology, which reveals a continuous search for the definition of the biological phenomenology in a manner such that would permit its complete explanation through well-defined notions and, accordingly, its complete validation in the observational domain. In this respect, evolutionary and genetic notions have been so far the most successful.

Yet these notions alone are insufficient because, although they provide a mechanism for historical change, they do not adequately define the basis of the biological phenomenology. In fact, evolutionary and genetic notions (by emphasizing generational change) treat the species as the source of all biological order, showing that the species evolves while the individuals are transient components whose organization is subordinated to its historical phenomenology. However, since the species is, concretely at any moment, a collection of individuals capable in principle of interbreeding, it turns out that what would define the organization of individuals is either an abstraction, or something that requires the existence of well-defined individuals to begin with. Where does the organization of the individual come from? What is the mechanism for its determination?

This difficulty cannot be solved on purely evolutionary and genetic arguments, since it is apparent to everyone (including evolutionists and geneticists) that any attempt to overcome it by resorting to other, comprehensive notions is doomed to failure if they do not provide us with a mechanism to account for the phenomenology of the individual. Such is the case when some sort of preformism is introduced by applying informational notions at the molecular level (nucleic acids or proteins); or when organismic notions are used that emphasize the unitary character of living systems but do not provide a mechanism for the definition of the individual. These notions fail because they imply the validity of the same notion that they are supposed to explain.

As is apparent from all that has been said, the key to the understanding of the biological phenomenology is the understanding of the organization of the individual. We have claimed that this organization is the autopoietic organization. Furthermore, we have shown that this organization and its origin are fully explainable with purely mechanistic notions that are valid for any mechanistic phenomenon in any space, and that once the autopoietic organization is established, it determines an independent phenomenological subdomain of the mechanistic phenomenology: the domain of the biological phenomena.

The development of the Darwinian notion of evolution, with its emphasis on the species, natural selection, and fitness, had an impact in human affairs that went beyond the explanation of diversity and its origin in living systems. It had sociological significance because it seemed to

offer an explanation of the social phenomenology in a competitive society, as well as a scientific justification for the subordination of the destiny of the individuals to the transcendental values supposedly embodied in notions such as mankind, the state, and society. In fact, the social history of man shows a continuous search for values that explain or justify human existence, as well as a continuous use of transcendental notions to justify social discrimination, slavery, economic subordination, and political submission of persons, individually or collectively, to the design or whim of those who pretend to represent the values contained in those notions. For a society based on economic discrimination, competitive ideas of power, and subordination of the citizen to the state, the notions of evolution, natural selection, and fitness (with their emphasis on the species as the perduring historical entity maintained through the dispensability of transient individuals) seemed to provide a biological (scientific) justification for its economic and social structure. It is known on biological grounds that what evolves is mankind as the species *Homo sapiens*. It is also known on biological grounds that competition participates in the specification of evolutionary change even in man. It is true that under the laws of natural selection the individuals most apt in the features which are favorably selected survive, or have reproductive advantages over the others, and that the others do not contribute or contribute less to the historical destiny of the species. Thus, from the Darwinian perspective it seemed that the role of the individual was to contribute to the perpetuation of the species, and that all that one had to do for the well-being of mankind was to let the natural phenomena follow their course. Science, biology, appeared as justifying the notion "anything for the benefit of mankind."

We have shown, however, that these arguments are not valid in justifying the subordination of the individual to the species, because the biological phenomenology is based on the autonomy of the individuals, and without individuals there is no biological phenomenology whatsoever. The organization of the individual is autopoietic, and upon this fact rests all its significance: it becomes defined through its existing, and its existing is autopoietic.

Thus in the realm of biology we see reflected the ethical and, ultimately, political choice of leaving out the view of the autonomy of things, whether animals or humans. The understanding of life becomes a mirror of our epistemological choices, which carry over to human actions.

6.3.2

A *phenomenological domain* is defined by the properties of the unity or unities that constitute it, either singly or collectively through their transformations or interactions. Thus, *whenever a unity is defined*, or a class

or classes of unities are established that can undergo transformations or interactions, *a phenomenological domain is defined*.

Two phenomenological domains intersect only to the extent that they have common generative unities, that is, only to the extent that the unities that specify them interact; otherwise they are completely independent, and obviously they cannot generate each other without transgressing the domains of relations of their respective specifications. Conversely, one phenomenological domain can generate unities that define a different phenomenological domain, but the new domain is specified by the properties of the new unities, not by the phenomenology that generates them. If this were not the case, the new unities would not in fact be different unities, but would be unities of the same class that generated the parental phenomenological domain; and they would generate a phenomenological domain identical to it.

Autopoietic systems do generate different phenomenological domains by generating unities whose properties are different from those of the unities that generate them. These new phenomenological domains are subordinated to the phenomenology of the autopoietic unities because they depend on them for their actual realization; but they are not determined by them: they are only determined by the properties of their originating unities, regardless of how these were originated. One phenomenological domain cannot be explained by relations that are valid for another domain; this is a general statement, which applies also to the different phenomenological domains generated through the operation of autopoietic systems. Accordingly, as an autopoietic system cannot be explained through statical or non-autopoietic mechanistical relations in the space in which it exists, but must be explained through autopoietic mechanistical relations in the mechanistical domain, so the phenomena generated through interactions of autopoietic unities must be explained in the domain of interactions of the autopoietic unities through the relations that define that domain.

6.3.3

The domain of *interactions* of an autopoietic unity is the domain of all the deformations that it may undergo without loss of autopoiesis. Such a domain is determined for each unity by the particular mode through which its autopoiesis is realized in the space of its components, that is, by its structural coupling. It follows that the domain of interactions of an autopoietic unity is necessarily bounded, and that autopoietic unities with different structures have different domains of interactions. Furthermore, an *observer* can consider the way in which an autopoietic system compensates its deformations as a *description* of the deforming agent that he sees acting upon it, and the deformation suffered by the system

as a representation of the deforming agent. However, since the domain of interactions of an autopoietic system is bounded, an observer of an autopoietic system can describe entities external to it (by interacting with them) that the system cannot describe, either because it cannot interact with them or because it cannot compensate the deformations which these cause.

The domain of all the interactions an autopoietic system can enter into without loss of identity is its *cognitive domain*; or, in other words, the cognitive domain of an autopoietic system is the domain of all the descriptions that it can possibly make. Accordingly, for any autopoietic system its particular mode of autopoiesis determines its cognitive domain and hence its behavioral diversity, and it follows that the cognitive domain of an autopoietic system changes along with its ontogeny and structural coupling.

We shall explore later in this book (Part III) the implications that the proper characterization of autonomy has within the domain of cognition. However, we anticipate here a few of these implications, in the light of the dependence of the cognitive domain upon the autopoietic organization of the individual.

The cognitive domain of any autopoietic system is necessarily relative to the particular way in which its autopoiesis is realized. Also, if knowledge is, in some suitable sense, *descriptive conduct*, then knowledge is relative to the cognitive domain of the knower. Therefore, if the way in which the autopoiesis of an organism is realized changes during its ontogeny, the actual knowledge of the organism (its descriptive repertoire) also changes; knowledge, then, is necessarily always a reflection of ontogeny of the knower, because ontogeny as a process of continuous structural change without loss of autopoiesis is a process of continuous specification of the behavioral capacity of the organism, and hence of its actual domain of interactions. Intrinsically, then, no "absolute" knowledge is possible, and the validation of all possible relative knowledge is attained through successful autopoiesis or *viability*.

6.3.4

Autopoietic systems may interact with each other under conditions that result in structural (behavioral) coupling. In this coupling, the autopoietic conduct of an organism *A* becomes a source of deformation for an organism *B*, and the compensatory behavior of organism *B* acts, in turn, as a source of deformation of organism *A*, whose compensatory behavior acts again as a source of deformation of *B*, and so on recursively until the coupling is interrupted. In this manner, a chain of interlocked interactions develops. In each interaction the conduct of each organism is constitutively independent in its generation of the conduct of the other, because it is internally determined by the structure of the behaving

organism only; but it is for the other organism, while the chain lasts, a source of compensable deformations that can be described as meaningful in the context of the coupled behavior. *These are communicative interactions*. If the coupled organisms are capable of plastic behavior that results in their respective structures becoming permanently modified through the communicative interactions, then their corresponding series of structural changes (which would arise in the context of their coupled deformations without loss of autopoiesis) will constitute two historically interlocked ontogenies that generate an interlocked consensual domain of behavior, which becomes specified during its process of generation. Such a *consensual* domain of communicative interactions, in which the behaviorally coupled organisms orient each other with modes of behavior whose internal determination has become specified during their coupled ontogenies, is a *linguistic* domain.

In such a consensual domain of interactions the conduct of each organism may be treated by an observer as constituting a connotative description of the conduct of the other, or, in his domain of description as an observer, as a consensual denotation of it. Thus, communicative and linguistic interactions are intrinsically *not* informative; organism *A* does not and cannot determine the conduct of organism *B*, because due to the nature of the autopoietic organization itself, every change that an organism undergoes is necessarily and unavoidably determined by its own organization. A linguistic domain, then, as a consensual domain that arises from the coupling of the ontogenies of otherwise independent autopoietic systems, is intrinsically noninformative, even though an observer, by neglecting the internal determination of the autopoietic systems that generate it, may describe it *as if* it were so. Phenomenologically, the linguistic domain and the domain of autopoiesis are different, and although one generates the elements of the other, they do not intersect.

Sources

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Chapter 7

The Idea of Organizational Closure

7.1 Higher-Order Autopoietic Systems

7.1.1

Whenever the conduct of two or more unities is such that there is a domain in which the conduct of each one is a function of the conduct of the others, it is said that they are coupled in that domain. Coupling arises as a result of the mutual modifications that interacting unities undergo in the course of their interactions without loss of identity. If the identity of the interacting unities is lost in the course of their interactions, a new unity may be generated as a result of it, but no coupling takes place. In general, however, coupling leads also to the generation of a new unity that may exist in a *different domain* in which the component coupled unities retain their identity. The way in which this takes place, as well as the domain in which the new unity is realized, depends on the properties of the component unities.

7.1.2

Coupling in living systems is a frequent occurrence, and the nature of the coupling of living systems is determined by their autopoietic organization. This is so because autopoietic systems can interact with each other without loss of identity as long as their respective paths of autopoiesis constitute reciprocal sources of compensable perturbation. Furthermore, due to their organization, autopoietic systems can couple and constitute a new unity while their individual paths of autopoiesis become reciprocal sources of specification of each other's environment, if their reciprocal perturbations do not overstep their corresponding ranges of tolerance for variation without loss of autopoiesis. As a consequence,

the coupling remains invariant, while the coupled systems undergo structural changes that are generated through the coupling and hence commensurate with it. These considerations also apply to the coupling of autopoietic and non-autopoietic unities, with obvious modifications in relation to the retention of identity of the latter. In general, then, the coupling of autopoietic systems with other unities, autopoietic or not, is realized through their autopoiesis. That coupling may facilitate autopoiesis requires no further discussion, and that this facilitation may take place through the particular way in which the autopoiesis of the coupled unities is realized has already been said. It follows that selection for coupling is possible, and that through evolution under a selective pressure for coupling a composite system can be developed (evolved) in which the individual autopoiesis of every one of its autopoietic components is subordinated to an environment defined through the autopoiesis of all the other autopoietic components of the composite unity. Such a composite system will necessarily be defined as a unity by the coupling relations of its component autopoietic systems in a space that the nature of the coupling specifies, and will remain a unity as long as the component systems retain their autopoiesis, which allows them to enter into those coupling relations.

7.1.3

A system generated through the coupling of autopoietic unities may, on a first approximation, be seen by an observer as autopoietic to the extent that its realization depends on the autopoiesis of the unities that integrate it. Yet, if such a system is not defined by relations of production of components that generate these relations and define it as a unity in a given space, but by other relations (either between components or between processes), then it is *not* an autopoietic system, and the observer is mistaken. The apparent autopoiesis of such a system is incidental to the autopoiesis of the coupled unities that constitute it, and not intrinsic to its organization; the mistake of the observer, therefore, lies in the fact that he sees the system of coupled autopoietic unities as a unity in his perceptive domain in other terms than those defined by its organization.

Contrariwise, if a system is realized through the coupling of autopoietic unities and is defined by relations of production of components that generate these relations and constitute it as a unity in some space, then it is an autopoietic system in that space, regardless of whether the components produced coincide with the unities that generate it through their coupled autopoiesis. If the autopoietic system thus generated is a unity in the physical space, it is a living system. If the autopoiesis of an autopoietic system entails the autopoiesis of the coupled autopoietic unities that realize it, then it is called an autopoietic system of *higher order*.

7.1.4

An autopoietic system can become a component of another system if some aspects of its path of autopoietic change can participate in the realization of this other system. As has been said, this can take place in the present through a coupling that makes use of the homeorhetic resorts of the interacting systems, or through evolution by the recursive effect of a maintained selective pressure on the course of transformation of a reproductive historical network that results in a subordination of the individual component autopoiesis (through historical change in the way these are realized) to the environment of reciprocal perturbations that they specify. Whichever is the case, an observer can describe an autopoietic component of a composite system as playing an *allopoietic role* in the realization of the larger system that it contributes to realizing through its autopoiesis. In other words, the autopoietic unity functions in the context of the composite system in a manner that the observer would describe as allopoietic.

Thus this allopoietic function is a feature of an alternative description by the observer, who changes the domain of description (from internal causal relations to external constraints) and the level of the system under consideration (from the autopoietic system as a unit, to the system plus its environment as a unit). To confuse these two forms of description would obscure both the mode in which an autopoietic unity becomes one, and the mode in which it can constitute a higher-order unity. The proper presentation of this feature of observation is through the duality of autonomy and control in the observer's cognition.

7.1.5

If the autopoiesis of the component unities of a composite autopoietic system conform to allopoietic roles that through the production of relations of constitution, specification, and order define an autopoietic unit, then the composite system becomes in its own right an autopoietic unity of second order. This has actually happened on Earth with the evolution of the multicellular pattern of organizations. When this occurs, the component (living) autopoietic systems necessarily become subordinated, in the way they realize their autopoiesis, to the constraints (maintenance) of the autopoiesis of the higher-order autopoietic unity which they, through their coupling, define topologically in the physical space. If the higher-order autopoietic system undergoes self-reproduction (through the self-reproduction of one of its component autopoietic unities or otherwise), an evolutionary process begins in which the evolution of the pattern of organization of the component autopoietic systems is necessarily subordinated to the evolution of the pattern of organization of the composite unity.

Furthermore, it is to be expected that if the proper contingencies are given, higher-order autopoietic unities will be formed through selection. In fact, if coupling arises as a way of satisfying autopoiesis, then the more stable that coupling is, the more stable will be any second-order unity formed from previous autopoietic systems. However, in an intuitive sense, a very stable condition for coupling appears if the unity organization is precisely geared to maintain this organization—that is, if the unity becomes autopoietic. It seems, then, that there is an ever-present selective pressure for the constitution of higher-order autopoietic systems from the coupling of lower-order autopoietic unities of higher order—a pressure imposed by the circumstances under which a unity can be specified in a given space.

7.2 Varieties of Autonomous Systems

7.2.1

Biological phenomena depend upon the autopoiesis of the individuals involved; thus, there are biological systems that arise from the coupling of autopoietic unities, some of which may even constitute autopoietic systems of higher order. What about human social systems: are they, as systems of coupled human beings, also biological systems? Or, in other words, to what extent are the relations that characterize a human society isomorphic to the autopoiesis of the individuals that integrate it?

The answer to this question is not trivial and requires considerations that, in addition to their biological significance, have ethical and political implications. This is obviously the case, because such an answer requires the *characterization of the relations that define a society as a unity* (a system), and whatever we may say biologically will apply in the domain of human interactions directly, either by use or abuse, as we saw with evolutionary notions. In fact, no position or view that has any relevance in the domain of human relations can be deemed free from ethical and political implications, nor can a scientist consider himself alien to these implications.

The difficulties of characterizing the defining relations and the extent of the implications of such characterizations extend to many kinds of unities that are part of, or close to, human life, such as families, ecosystems, economies, managerial complexes, nations, clubs—in brief, every natural system. As in the case of living systems, what is apparent is a *degree of autonomy* in the way such unities are present in our experience. They have defined a domain or space in which they exist (usually not the physical space), and they have components that integrate them and relations among these components such that the unity attains coherence and can be distinguished through the interdependence of components. How are we to deal with this variety of autonomous systems?

7.2.2

In general, the actual recognition of an autopoietic system poses a cognitive problem that has to do both with the capacity of the observer to recognize the *relations* that define the system as a unity, and with his capacity to distinguish the *boundaries* that delimit this unity in the space in which it is realized (his criteria of distinction). Since it is a defining feature of an autopoietic system that it should specify its own boundaries, a proper recognition of an autopoietic system as a unity requires that the observer perform an operation of distinction that defines the limits of the system in the same domain in which it specifies them through its autopoiesis. If this is not the case, he does not *observe* the autopoietic system as a unity, even though he may *conceive* it. Thus, in the present case, the recognition of a cell as a molecular autopoietic unity offers no serious difficulty, because we can identify the autopoietic nature of its organization, and can interact visually, mechanically, and chemically with one of the boundaries (membrane) that its autopoiesis generates as an interface to delimit it as a three-dimensional physical unity.

7.2.3

What other autonomous systems have in common with living systems is that in them too, the proper recognition of the unity is intimately tied to, and occurs in the *same* space specified by, the unity's organization and operation. This is precisely what autonomy connotes: assertion of the system's identity through its functioning in such a way that observation proceeds through the coupling between the observer and the unit in the domain in which the unity's operation occurs.

What is unsatisfactory about autopoiesis for the characterization of other unities mentioned above is also apparent from this very description. The relations that characterize autopoiesis are relations of *productions* of components. Further, this idea of component production has, as its fundamental referent, chemical production. Given this notion of production of components, it follows that the cases of autopoiesis we can actually exhibit, such as living systems or model cases like the one described in Chapter 3, have as a criterion of distinction a topological boundary, and the processes that define them occur in a physical-like space, actual or simulated in a computer.

Thus the idea of autopoiesis is, by definition, restricted to relations of productions of some kind, and refers to topological boundaries. These two conditions are clearly unsatisfactory for other systems exhibiting autonomy. Consider for example an animal society: certainly the unity's boundaries are not topological, and it seems very farfetched to describe social interactions in terms of "production" of components. Certainly these are not the kinds of dimensions used by, say, the entomologist studying insect societies. Similarly, there have been some proposals

suggesting that certain human systems, such as an institution, should be understood as autopoietic (Beer, 1975; Zeleny and Pierre, 1976; Zeleny, 1977). From what I said above, I believe that these characterizations are category mistakes: they confuse autopoiesis with autonomy. I am saying, in other words, that we can take the lessons offered by the autonomy of living systems and convert them into an operational characterization of *autonomy in general*, living and otherwise.

7.2.4

Autonomous systems are mechanistic (dynamic) systems defined as a unity by their organization. *We shall say that autonomous systems are organizationally closed. That is, their organization is characterized by processes such that (1) the processes are related as a network, so that they recursively depend on each other in the generation and realization of the processes themselves, and (2) they constitute the system as a unity recognizable in the space (domain) in which the processes exist.*

Several comments are in order:

1. The processes that specify a closed organization may be of any kind and occur in any space defined by the properties of the components that constitute the processes. Instances of such processes are production of components, descriptions of events, rearrangements of elements, and in general, computations of any kind, whether natural or man-made. In this sense, whenever the processes are defined and their specificity is introduced in the characterization of organizational closure, a particular class of unities is defined. Specifically, if we consider processes of production of components, which occur in the physical space, organizational closure is identical with autopoiesis.
2. The processes that participate in systems may combine and relate in many possible forms. Organizational closure is but *one* form, which arises through the circular concatenation of processes to constitute an interdependent network. Once this circularity arises, the processes constitute a self-computing organization, which attains coherence through its own operation, and not through the intervention of contingencies from the environment. Thus the unity's boundaries, in whichever space the processes exist, is indissolubly linked to the operation of the system. If the organization closure is disrupted, the unity disappears. This is characteristic of autonomous systems.
3. We can interact with and recognize an autonomous system because there is a criterion for distinguishing it in some space. However, if such a distinction is, at closer inspection, not associated with the system's operation, then either the unity is not organizationally closed, or else the observer is describing it in a dimension that is not the one in which the organizational processes occur. Only when organization

and distinction are linked do we have an autonomous system, and this can only occur through organizational closure.

4. In a sense, the idea of organizational closure generalizes the classical notion of stability of a system that cybernetics inherited from classical mechanics, proposed by Androsov and Pontriagyn in the 1930s. This is so to the extent that one can, in this formalism, represent a system as a network of interdependent variables, whose pattern of coherence (in the stable trajectories of the phase space) affords a criterion of distinction (the variables are assumed to be observables). Many models of this sort exist in the literature, among them the hypercycle studied by Eigen and Schuster (1978).

Thus, in some instances, the stability of a dynamical system can be taken as a representation of the organizational closure of an autonomous system. But these two ideas, dynamical stability and organizational closure, are not to be confused, the former being a specific case of the latter since stability is a particular rendering of invariance. In fact, the framework of differentiable dynamics that gives rise to the notion of stability cannot accommodate a number of mechanistic systems that are of interest to us in general (such as nervous systems, conversations, and the like), because they are some levels removed from their physico-chemical underpinnings. Further, in this classical representation, the interdependence of the processes is not made explicit but remains implicit in the formalism, so that the very mechanism of autonomy is obscured. These limitations are reflected very dramatically in previous attempts to use the differentiable approach for a general treatment of autonomous, viable natural systems (e.g. Iberall, 1973). We shall return to this question of formalization of autonomy later on, in Chapters 10 and 13 (see especially Section 13.11.1).

In a very similar vein, organizational closure is close to, but distinct from, feedback, to the extent that the latter requires and implies an external source of reference, which is completely absent in organizational closure. A network of feedback loops mutually interconnected is organizationally closed, and in fact, this sort of analysis can be useful in some cases. But what we should never forget is that one of the central intentions of the study of autopoiesis and organizational closure is to describe a system with no input or outputs (which embody their control or constraints) and to emphasize their autonomous constitutions; this point of view is alien to the Wienerian idea of feedback *simpliciter* (cf. Bateson, 1977).

In the present approach, the notion of stability is generalized to that of *coherence* or *viability understood as the capacity to be distinguished in some domain*, and the representation of such coherence is generalized to any form of indefinite recursion of defining processes such that they generate the unitary character of the system.

5. In the characterization of organizational closure, nothing prevents the observer himself from being part of the process of specifying the system, not only by describing it, but by being one link in the network of process that defines the system. This situation is peculiar in that the describer cannot step outside of the unity to consider its boundaries and environment simultaneously, but it is associated with the unit's functioning always as a determining component. Such situations, to which most of the autonomous social systems belong, are characterized by a dynamics in which the very description of the system makes the system different. At each stage, the observer relates to the system through an understanding, which modifies his relationship to the system. This is, properly speaking, the hermeneutic circle of interpretation-action, on which all human affairs are based.
6. As in the case of autopoiesis, the organizational closure generates a unity, which in turn specifies a phenomenological domain. Thus with each organizational closed class of unities a unique phenomenology is associated. Whenever such phenomenology is extensive, in diversity and importance, a proper name is given both to the phenomenology and the kind of organizational closure, as in the case of autopoiesis and biological phenomenology. Another example is closure through linguistic interactions and the phenomenology of communication.

Furthermore, it is clear that once a unit is established through closure, it will specify a domain with which it can interact without loss of its closure or loss of identity. Such a domain is a domain of descriptive interaction relative to the environment as beheld by the observer, that is, is a *cognitive domain* for the unity. Mechanisms of identity, the generation of phenomenology, and a cognitive domain are all related notions that are grouped around the specification of an organization through closure in a given domain.

7.2.5

The role that living systems play in the characterization of organizational closure is one of *paradigmatic case*. Autopoiesis is a case of, and not synonymous with, organizational closure, and the autonomy of living systems is a case of, and not synonymous with, autonomy in general. However, because of the kind of detail we have in our knowledge of living systems, and because there are some particularly minimal cases such as the cell, the basis of autonomy is clearer in living systems, whence their exemplary character. There is a mass of experience and tradition in biology that suggests and confirms the autopoietic nature of the living organization.

Furthermore, it would seem that in all natural systems so far studied in any detail, the recursive interdependence of their processes has been revealed. To substantiate this claim, it is not possible to simply go through

empirical evidence in different fields. This is so because the way in which empirical evidence is organized is, in itself, a function of the basic theoretical perspective one adopts. Thus our approach proceeds in the opposite direction: we will make this background of knowledge into a theoretical assumption, and then proceed to apply it to several domains and prove its validity by means of its fertility.

This basic theoretical assumption, I now make explicit in the following:

Closure Thesis

Every autonomous system is organizationally closed.

By a "Thesis" I mean here a heuristic guide, based on empirical evidence, that gives some precise meaning to an intuitive notion. In this sense is similar to Church's Thesis in the theory of computation, where the vague notion of computability is made equivalent to that of a recursive function, because nothing that, in our culture, is consensually accepted as an effective procedure has ever been found not to be reducible to a recursive function. Similarly here, the vague notion of autonomy is made equivalent to that of organizational closure, because of our previous knowledge of autonomy of natural systems. The task is, then, to use the idea of organizational closure and its consequences to explore the phenomena of autonomy.

7.2.6

There are paramount consequences if a system exhibits organizational closure. This is so because closure and the system's identity are interlocked, in such a way that it is a necessary consequence for an organizationally closed system to subordinate all changes to the maintenance of its identity. This we discussed extensively in relation to living systems, and again, their behavior can be taken as paradigmatic. What is seldom realized is that if we can legitimately say that, for example, a corporate structure has organizational closure, the same kind of self-maintenance of identity will carry over unchanged to this phenomenological domain. This is *not* to say that some social systems are living systems and behave as such, as has been so often stated: it means that organizational closure generates a domain of *autonomous behavior* in this unity that is livinglike, but of quite different characteristics. The practical consequences of this view of social situations are, I believe, quite dramatic, for it forces on us to distinguish very clearly between the organization of, say a corporation, and the purpose that is ascribed to it. If the corporation exhibits closure, no matter what our description of the system's purpose is, its behavior will be such that all perturbations and changes will be subordinated to the maintenance of the system's identity. This is so even when we may

treat perturbations from the environment as controlling inputs. Such controlling inputs belong to an alternative description of the system (cf. Chapter 10), revealing a phenomenology that is complementary, but not reducible, to its autonomous behavior. For such systems, all apparent informational exchanges with its environment will be, and can only be, treated as perturbations within the processes that define its closure, and thus no "instructions" or "programming" can possibly exist. The observer may change his descriptions and consider the regularities between ambient perturbations and the system's regularities in compensations, but all interpretations of such regularities as information flow are relative to the system's closure and can only be understood in reference to its functioning.

It is just as well to realize, with these considerations, that this revision of control and information has ethical and political implications that are very concrete and cannot be avoided. I will *not* discuss them in this book at any length. I do want to make it clear that the idea of autonomy and its consequences are *not* restricted to biological, natural systems, but can encompass human and social systems *as well*. Here, I can only phrase the arguments for biological cases and draw the epistemological inferences. This represents, not a limitation of the applicability of the ideas, but a limitation of my ability to cover the subtleties of the extension to the social realm. Others have been more articulate about some of these implications. For a discussion on the specific ideas of autonomy and closure for socio-political systems see Bråten (1978), Alker (1976), Beer (1972, 1975a,b), Schwember (1976), Burns (1976), and most especially the work of Dupuy and Robert (1976, 1978), which studies the way in which control notions shape the delivery of social services. Other, more general discussions in consonance with the questions discussed here are Goffman (1974), Berger and Luckman (1966), Morin (1975, 1977), Castoriadis (1975), Flores and Winnograd (1979), and Moscovici (1968, 1972).

7.2.7

The detailed discussion of autonomy of living systems, their characterization as autopoietic systems, and the generalization of the autonomy of living systems to the Closure Thesis, has set a clear agenda for the remainder of our investigation. There are two distinct themes that interpenetrate. On the one hand, there is the role and presence of the observer, who sets criteria for distinctions in different domains and is capable of alternative descriptions or different views of a system. On the other hand, there is the role of recursive, self-referential phenomena in determining a system's identity, which generates, for each class of unities, a cognitive domain. These two main themes converge and become operationally one in the cases where the describer and system's processes are

the same. These topics we will consider successively in the chapters that follow.

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PART II

DESCRIPTIONS, DISTINCTIONS, AND CIRCULARITIES

Die Fehler der Beobachter entspringen aus den Eigenschaften des menschlichen Geistes. Der Mensch kann und soll seine Eigenschaften weder ablegen noch verleugnen. Aber er kann sie bilden und ihnen eine Richtung geben. Der Mensch will immer tätig sein.

J. W. Goethe, *Beobachtung und Denken* (circa 1794)

A universe comes into being when a space is severed or taken apart. . . . By tracing the way we represent such a severance, we can begin to reconstruct, with an accuracy and coverage that appears almost uncanny, the basic forms underlying linguistic, mathematical, physical, and biological science, and can begin to see how the familiar laws of our own experience follow inexorably from the original act of severance.

G. Spencer-Brown, *Laws of Form* (1969)