A Brief History of the BCL

Heinz von Foerster and the Biological Computer Laboratory

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"Heinz, where would a historian have to begin if he wanted to tell the story of the BCL?"
"He'd have to start with the Macy Conference."[1]

Before following this thoroughly sound piece of advice, I would like to briefly describe the goal I have set for myself here. I am attempting a preliminary interpretation of a small and, as I believe, unusual chapter of the history of science from the late 1950s to the mid-1970s, one that has received little attention up to now.

And I am equally motivated by the fact that the BCL has very seldom been mentioned[2] in the literature on the history of cybernetics, systems theory, bionics (now the subject of renewed debate), parallel computing, neurophysiology, bio-logic, artificial intelligence, symbolic computing, or constructivism as an intellectual tradition—and it would be possible to list even more areas of science that are renowned today—despite the fact that workers at this institution, the BCL, figure importantly in the literature on each of these domains. Is this an oversight specifically on the part of the history of science (the forgetfulness of science itself being well known)?[3] I am not sure. Let me try to give an example from a specific field: anyone who takes even a passing interest in the history of cybernetics will immediately encounter the name of its founder, Norbert Wiener.[4] At the same time, it will be learned at once that Wiener was active at the Massachusetts Institute of Technology (MIT). Soon afterwards, the interested party will encounter the name of W. Ross Ashby, the author of what is still one of the most important textbooks on the foundational principles of cybernetics—beautifully written and still worthy of study today.[5] Our interested party will further learn that Ashby was an English psychiatrist. However, he probably will not learn that until 1972 Ashby held a long-standing professorship at the BCL. Among other things, such small details are what have led me to work on a preliminary short history of the BCL.[6]

BCL (Biological Computer Laboratory) was the name of an independent division within the Department of Electrical Engineering at the University of Illinois. The BCL was founded in 1957/58 by Heinz von Foerster, who at that time was Professor of Electrical Engineering in the department, and was closed after his retirement. The hypothesis thus suggests itself at once that the fate of this institution was closely connected to that of its founder and director.[7]

Prehistories

For every brief history, a brief prehistory can be told. In the case of the BCL, this prehistory will necessarily focus on the biography of its founder. Not long after arriving in the United States in 1949, Heinz von Foerster was appointed to a position at the University of Illinois. At first, this was the result of a series of accidents, followed by strong support from Warren McCulloch. In 1949, Foerster was not a scientist in the strict sense of the word, either according to Central European standards or to American ones. He was, rather, a technician and an inventor. Before 1945, he had worked in the area of advanced basic research in physics, directed towards weapons research for the National Socialist regime.[8] For various reasons, he did not have a regular academic degree,[9] and up to that time he had published little: an article on physics,[10] and a small book that was considered a work of psychology according to the standards of its time and place.

After 1945, he earned half his living as a technician in a Vienna company for communications technology. He earned the other half of his living as a journalist, covering both sociopolitics and scientific developments for the Rot-Weiss-Rot radio station. At that time, science was something like a hobby for Foerster—even his first book publication, Das Gedächtnis [Memory], was a side project.[11] In post-WWII Vienna, this publication met with only lukewarm approval,[12] even among psychologists[13]—although it did attract the interest of, for example, Erwin Schrödinger.[14]

Via private channels, this study happened to fall into the hands of Warren McCulloch, who hoped to find in its quantum-mechanical approach a solution to some research problems that were unknown to Foerster when he was writing Das Gedächtnis. McCulloch[15] invited Foerster to present his ideas about the functioning of memory with regard to remembering and forgetting to a cybernetics conference—the Macy Conference.[16]

Unlike the BCL, the Macy Conference meetings have received attention from historians of science. A good example of this is Steve Heim's book on the Cybernetics Group 1946-1953.[17] This work is based on a broad knowledge of sources, but suffers somewhat from its ideological fixation on the United States and the Cold War. In the book, political developments in the United States are sometimes connected too closely to the activities of this research group.

After his first presentation at the Macy Conference in 1949, Heinz von Foerster was appointed editor of the publication of the conference proceedings.[18] In a very short time, he had moved from the remote periphery (post-war Vienna) to the center of one of the most important scientific movements of the 20th century.

In 1949, the Macy Conference participants represented the fields of psychiatry, electrical engineering, physiology, computer science, medicine, zoology, psychology, sociology, ethnology, anatomy, neurology, behavioral sciences, mathematics, radiobiology, biophysics, and philosophy. By 1953, this list had expanded to include economics and other disciplines.[19]

Besides conference chairman Warren McCulloch, the participants included Norbert Wiener, John von Neumann, Gregory Bateson, Margaret Mead, Julian H. Bigelow, Paul Lazarsfeld, Walter Pitts, and the leader of the Macy Foundation conference program, Frank Fremont Smith.

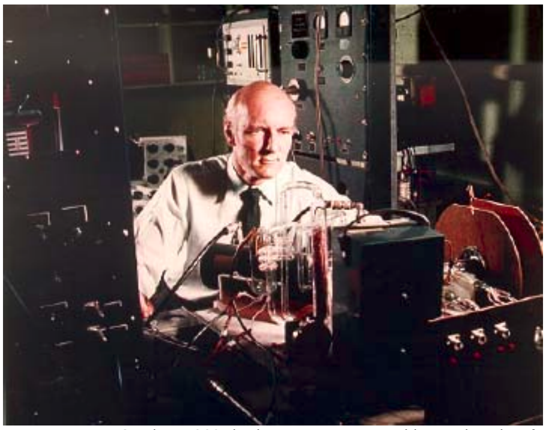
In the discussions held by this group, Heinz von Foerster proved to be "cooperative, not competitive."[20] The publications that appeared under his editorship sought to reproduce this structural feature of the discussions in printed form. The lectures were interrupted by questions, requests for explanations, objections, etc., emphasizing the multiple perspectives on the subject under discussion. However, this cooperative mode of discussion is also susceptible to strong objections. One example of this is the disagreement between Ross Ashby, who presented his examples of homeostasis, and Julian Bigelow, who vehemently disputed the usefulness of this construct.[21]

For Foerster, who from this point onward held the post of Professor of Electrical Engineering in Urbana, Illinois, the participation in these regular yearly conferences provided something like an intellectual center. After the end of the Macy group (in 1953), he tried to find a way to carry its legacy onward. As a physicist in Urbana, however, Foerster first held a position connected to his earlier work: he was the director of the Electron Tube Lab.

The founding of the BCL

For Foerster, one of the most promising paths for cybernetics was clearly to be sought in the full exploration of its possible applications. However, at first these applications were not the results of Foerster's earlier research as a physicist and electrical engineer. He took advantage of a sabbatical and the support of the Guggenheim Foundation to broaden his education into other areas. For example, at MIT he studied problems of neurophysiology with Warren McCulloch, and he also traveled to Mexico in order to work on problems in physiology and biology with Arturo Rosenblueth, an important member of the Macy group. During this trip, among other things he produced a manuscript, unpublished at the time, on the cybernetics of muscular activity.[22]

After this "training" with Rosenbleuth and McCulloch, Foerster's legitimacy was sufficiently well-established for his university to grant him the freedom to open and operate the BCL entirely as he saw fit, as far as I can tell. The laboratory opened on January 1, 1958. This marked the beginning of a completely new branch of research within the university and within the department of electrical engineering. Foerster gave up the leadership of the Electron Tube Lab, which in any case was losing relevance due to the increasing significance of transistors.



Heinz von Foerster at BCL circa 1960. (Heinz von Foerster Archive, University of Vienna.)

In its first decade, the BCL was above all a research laboratory. Almost no teaching duties were connected with the work there. Students working at the BCL were paid in the context of research projects, and did not receive a formal education in the sense of a course of study or curriculum.

The BCL was financed primarily by third parties. Apart from medical and other programs, the U.S. Air Force and the U.S. Navy were the main financial supporters of the laboratory (see Table 2 below). In the 1950s and 1960s, both of these branches of the military had enormous budgets for non-military basic research. This did not change until the early 1970s.

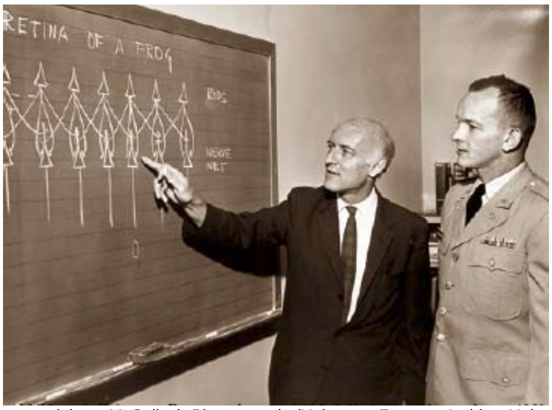
Early years

In attempting to reconstruct the early years of the BCL, the following noteworthy results emerge. Foerster was clearly very quickly able to bring interesting researchers to the BCL. Some of these, such as Ross Ashby, came from the cybernetic “establishment,” but representatives of more “remote” disciplines, such as the philosopher Gotthard Günther, were also attracted. And young scientists from all areas of science continued to come. The BCL also invited guests. Such invitations were probably only partly “strategic,” being also partly accidental or mediated via already-existing channels, not least the Macy group. For example, Gotthard Günther came to the BCL through the agency of Warren McCulloch.[23] In the first years of the laboratory, up to 1965, the following were invited as Visiting Research Professors: Gordon Pask (England), Lars Löfgren (Sweden), W. Ross Ashby (England), Gotthard Günther (US / Germany), William Ainsworth (England), Alex Andrew (England), and Dan Cohen (Israel). Permanent professorships went to Ashby (beginning in 1961) and Günther (beginning in 1967). Pask,[24] with whom Foerster authored some joint publications,[25] and Löfgren remained in permanent contact with the BCL.

Self-organizing systems and bionics

On the basis of this foundational structure, the BCL was able after a very short “warm-up period” to engage with one of the most salient and promising issues of the day, and also to fill many positions in its organization. A number of important conferences were held in the BCL environment. Thematically, these were organized around problems of systems theory, specifically the field of self-organizing systems.[26] Today, the volumes containing the proceedings of these conferences, such as Self-Organizing Systems[27] or Principles of Self-Organization,[28] are still of fundamental importance for this area of research. These conferences, and subsequent ones in which members of the BCL participated, quickly attracted international attention, and their effects spread by diffusion through European countries up to and including the USSR. The theory of self-organizing systems both contrasted with and expanded the tradition of systems theory,[29] going back to the 1920s, and in particular broadened its areas of application enormously. Heinz von Foerster’s contributions here consisted above all in the concept of order from noise, and in the analysis of self-organizing systems in the context of thermodynamics.[30]

Besides systems theory and self-organization, the buzzword “bionics”[31] was primarily responsible for attracting attention to the BCL research group. “Bionics” was a general catchword that covered attempts to analyze biological processes, to formalize them and to implement them on computers.[32] Here the BCL followed the ideas of McCulloch and Pitts,[33] as well as the tradition of the Macy conferences. Symposiums and conferences on bionics were also held, and had an international influence. The term “bionics” also represented an alternative to the idea of “artificial intelligence,” formulated in 1956,[34] although today it is clear that in the long run artificial intelligence has been a more successful concept in scientific research programs.



Heinz von Foerster explains a McCulloch-Pitts network. (Heinz von Foerster Archive, University of Vienna.)

The rapid success of the BCL also had the result that military resources were made available to the laboratory, although the BCL never supplied products that were used or considered valuable by the military. However, besides basic research, application-oriented research was also carried out at the BCL. This included, for example, an interdisciplinary project on leukocyte research[35] and a series of demographic studies on the outlook for global population. The so-called Doomsday Project[36] garnered publicity beyond specialist circles, not least because into the 1980s it provided better predictions than did traditional demography.[37]

About both projects, and other ones as well, it could be said (and has been said) that they were based on the unorthodox, “oblique” ideas of Heinz von Foerster. When brought into the terminology of innovation research,[38] this informal formulation, intended merely as a label for the strategic application of research strategies to unexpected or surprising areas, makes it possible to view recombination as a central element of scientific creativity at the BCL. It is no accident that the idea of “Foerster operators” emerged in this context.[39]

Deviation as innovation

“Deviant” hypotheses and research programs became increasingly characteristic for the BCL style, or the research style of its protagonists. A departure from the mainstream of research was clearly not the intended goal, but was the obvious result of the next phase of the history of the laboratory, whose beginning can be dated to the mid-1960s. At that time, Heinz von Foerster visited the Chilean scientist Humberto Maturana, whom he had met at a conference in Europe, at his laboratory in Santiago, and subsequently invited him to the BCL. Maturana had already been to the United States, having worked for some time at MIT, where he had not fit in so well due to his "stubborn" opinions. At that time (in 1959), he already had a difficult relationship with the laboratory of Marvin Minsky, the later "mastermind" of artificial intelligence research.[40] So Maturana came to the BCL, where he worked on, among other things, an important article leading toward his now-famous theory of autopoiesis.[41] Even the earliest formulation of the theory of autopoiesis, as it was later articulated, appeared first as an internal publication of the BCL.[42] Students and co-workers of Maturana also developed ties to the BCL, and centrally important first publications—for example, those of Francisco Varela—were published as BCL reports. The contacts that led to publication in English were made at the BCL.

It was probably the challenge provided by the impetus of the Chilean group that enabled Heinz von Foerster to push ahead with the development of his radical version of a "second-order cybernetics."[43] This does not mean that Foerster's concepts could be derived from those of Maturana, or vice versa. The parallels and the mutual stimulation could be seen at a 1969 conference on Cognitive Studies and Artificial Intelligence Research. Foerster's contribution can be read as a direct response to that of Maturana, and vice versa.[44] The main parallel between Foerster and Maturana seems to consist in the self-thematizing turn, which was directed against the scientific mainstream in the 1960s and early 1970s. Two leitmotifs can be seen here—that of "closing" and that of the "observer."

Towards the end of the 1960s, there was a decided movement in the direction of the problem of language, if not a "linguistic turn" in the usual sense of that phrase. Both "linguistics" and "speech" became important areas of research, under five main thematic areas of emphasis. A table from 1969 indicates the structure of BCL research at that time (see Table 1). The general subject areas are logic, linguistics, structure and function of systems, speech (i.e., spoken language), and physiology.

Table 1. Research structure of BCL, 1969

	Foundations	Theory	Computation	Equipment	Experiments
Logic	• Natural numbers in transclassic systems				
Linguistics	• Computers and language, linguistics, grammar				
Structure and Function of Systems	• Complex dynamic systems • Self-reproduction	• Automata theory • Complex systems analysis • Computational networks • Cognition and perception • Neurons and nets • Teaching machines • Information transducers	• Automata theory • Computational networks • Neurons and nets	• Teaching machines	• Teaching machines
Speech		• Speech event sequences • Speech analysis • Response distortion of a network • Adaptive sampling of speech • Speech synthesis		• Speech event sequences • Speech analysis • Response distortion of a network • Adaptive sampling of speech • Speech synthesis	• Speech event sequences • Speech analysis • Response distortion of a network • Adaptive sampling of speech • Speech synthesis
Physiology		• Tectal organization of ambystoma tigrinum • Display of neurophysiological data • Endocrine modeling	• Display of neurophysiological data	• Display of neurophysiological data	• Tectal organization of ambystoma tigrinum • Display of neurophysiological data • Endocrine modeling

Deviation and innovation: The turn toward the social

In the late phase of the BCL, attempts were made to find practical social applications both for already-achieved insights and for planned further developments. Particularly noteworthy here is a series of projects in which the main emphasis was on social utility. Existing elements, such as cognitive and information-theoretical studies, the modeling of the sensory apparatus, studies on data structure and general questions of problems in contemporary society were to be in a certain sense "merged" in order to produce results having general practical usefulness, above all for society.

"The question of applications in the social sphere was a problem to which I was attracted quite early on. I and my friends always regarded the social problem as having to do with the possibility of a linguistic connection. We saw language as the glue that forms a society. […] Language makes second-order communication possible. […] One of the members of our group who was the best at reflections on language was Paul Weston."[45]

Under the title "Direct Access Intelligence Systems,"[46] an attempt was made to create a kind of "intelligent" database, whose key characteristics were to be non-numerical content, a natural-language interface, and networked, decentralized knowledge bases. "Our idea was that the interface had to be built so that I could remain as I already am and the system could remain as it was already running."[47]

In the development of these projects, the interdisciplinary base was again broadened, and a working group for Cognitive Studies was founded, which included, for example, educational theorists.

Besides the two projects proposed by Foerster in 1970 and 1971, BCL theorist Paul Weston also formulated a proposal that primarily had to do with data structures, or what we would today call information design.[48] Reading these forward-looking proposals more than 30 years later, one is reminded of advanced, non-commercial conceptions of what was to become the Internet.

The assumption behind these projects was that individual members of society had a knowledge deficit relative to the knowledge base of the collective as a whole. The projects envisioned terminals in the sphere of the users' everyday lives. The SOLON system was to be accessed via natural language. The user would receive either the required answer or a further question that would lead toward a solution. The question itself would become part of the database.

In connection with such a project, the question still arises today—as it did for the experts who at the time reacted skeptically—of the possibility of realizing such a system: "This problem still has not been solved. In retrospect, what do you think the chances were that you could have solved this problem?" "Extremely good. If we had been able to pursue the work further, we could have brought fascinating results to the table."[49]

The anonymous, unfavorable expert opinions that the research group received also shed an interesting light on the precariousness of multidisciplinary research, as can be seen in the negative, or at least reserved, reactions of representatives of the individual disciplines.

For example, one expert commentator, who described himself as "deeply involved in the physiological basis of perception and the mechanisms of attention and decision making," stated: "I cannot escape the conclusion that cognition laboratories equipped with the machines proposed by Dr. von Foerster cannot cope effectively with even the known range of states and transitions in human perception and cognition." An (obvious) computer expert suggested, on the other hand, that what was needed was to use a different programming language. A (presumed) social scientist doubted the social utility of a project that concerned itself primarily with the nature of cognition. And one commentator, who in various details betrayed a familiarity with the projects of Terry Winograd and Seymour Papert, and thus (in 1972) a certain proximity to MIT, rejected the project categorically: "I find the proposal incredible, so incredible that I hardly know how to describe my reaction."[50]

Publications

The list of individual scientific achievements must here remain incomplete and cursory. For the laboratory as a whole, some publication indicators may be cited. The publications of the BCL are well-documented and are available for viewing on microfiche in Europe as well as in the US.[51]

Here, then, let a few statistics suffice. The official list of BCL publications includes just over one hundred authors. The list includes all the works that can be attributed to the BCL: books, articles, and unpublished research reports of the professors, workers, students and guests. The number of works per author varies greatly. The lowest such number is one. These cases are usually the final thesis of a student. At the top of the scale, we find, unsurprisingly, Heinz von Foerster, with just over one hundred publications from 1957 to 1976. The average number of publications per author is six. (In calculating this number, publications having multiple authors were credited to each of the authors.)

The thematic breadth of these publications is astonishing. They include scientific disciplines such as mathematics, physics, medicine, biology, and biochemistry, and technical disciplines such as computer science, but also philosophy, logic, linguistics, communication theory, political science, pedagogy, and social sciences. The list also includes anthropology (Heinz von Foerster also served for a time as president of the Wenner-Gren Foundation), musicology, music theory/composition,[52] and dance. And I am certainly leaving some out.

The publications therefore reflect a fascinating praxis of transdisciplinary work, which strongly recalls the milieu of the Macy conferences. Looking at the development of the laboratory over time, we note that the transdisciplinarity increases, or, otherwise formulated: the coefficient of disciplinary disparity, as we may call it, becomes greater. This was clearly due to a number of factors:

- a deep mistrust of the possibilities and problem-solving abilities of the individual disciplines;
- the need to bring insights from cybernetics, especially second-order cybernetics, into the individual disciplines;
- the possibility of using the individual disciplines to contribute to the further development of cybernetics.

This radical emphasis on transdisciplinarity, as practiced at the BCL, creates chances for innovation, but it also carries possible risks, at least in the context of science as it is practiced today. Since the 1990s, an enormous discussion has again arisen concerning the boundaries of disciplines.[53] The risks include, among others, surrendering one's own identity, and thus shrinking the core competences that one is ascribed.

The estimated number of publications relating to "useful" or "immediately usable" research results was higher in the early years of the laboratory than in later years. Thus, studies on cell multiplication in medicine were "applied," while the practical utility of articles focused more strongly on general epistemology was less apparent. And in the work of Heinz von Foerster, it was precisely this interest in epistemology that came more strongly to the fore at the same time as his interest in solving social problems—not least due to the "atypical" environment of the BCL. If one were so inclined, it would be possible to try to ground this development as well in the logic of the work, as it were. But in an environment that placed a high value on an engineering spirit, directed to practical and above all commercially applicable scientific work, the understanding required for this development was clearly lacking. Highly interesting work was done at the BCL on computing in the semantic domain,[54] but apart from prototypes this never translated into a technical/industrial realization in hardware or software.

Prototypes

The prototypes developed at the BCL over the course of its history included for example artificial neurons, the Numarete device, the social interaction experiment, and the dynamic signal analyzer, described in 1965.[55] In 1966 the Visual Image Processor was presented.[56] In 1967, a speech decoder and a real-time speech processor were mentioned.[57] Roughly, the machines built at BCL in the 1960s could be described as "perception machines."

The most interesting of these was the Numarete. A first publication about it appeared in 1962, after a report on it had been presented at a conference in 1960.[58] The Numarete, various versions of which have been documented, was able to recognize the number of objects "shown" to it. It was based on a simulation of a network of Pitts-McCulloch cells, which operated through a special arrangement and interconnection of photovoltaic cells with flip-flops, which are electronic elements that can assume one of two states (on or off, or 0 and 1). The Numarete was a computer that was not built according to the (reductionistic) von Neumann architecture, but rather was in a sense "oblique" to this architecture: it was based on the parallel operations of its modules.

Conflicts

Beginning in the late 1960s, conflicts arose between the BCL and the university administration. BCL workers were, like Foerster himself, incorporated into the university's general teaching structure, and worked on participatory teaching projects that were quite unorthodox in their environment but that corresponded well to the general climate of student rebellion at that time. Responding to student demand, a course in "Heuristics" was offered.[59] One of the goals of this course was not only to have the students participate actively, but to make them aware of their individual responsibility for the course, and to have the course culminate in a "product" to which they could all contribute. This product was a joint publication having the title "The Whole University Catalogue."[60] Against this publication, the objection was raised that it contained obscenities and dealt with drug use.[61] Protests by parents' groups led ultimately to Foerster's having to justify himself at a hearing. Despite this resistance, the principles developed in the Heuristics course were retained in its teaching.

The course "Cybernetics of Cybernetics" (1973-74) was also conducted according to a similar participatory model. The publication resulting from this course still provides a useful compendium of the field, because it contains definitions that remain valid, as well as reprints of important articles. The stronger involvement in teaching, in combination with innovative pedagogical approaches, also had the effect of providing a kind of summary and articulation of the work of the BCL.[62]

An excellent group culture—and an unstable communication structure?

In many ways, the "group culture" of the BCL was seen as, for its time (and not only for its time), unusually liberal, open, and "heterarchical," in connection with its already-discussed inter- or transdisciplinary breadth. In many ways, the leader of the lab was himself also seen as the originator of this structure. At the same time, it appears to have been the case that not all the BCL members took advantage of the possibilities that this structure offered. "Heinz was the crossing point of all these studies going on in the BCL," according to Humberto Maturana, who was a guest and lecturer at the BCL. "I don't remember that there has been something that one would call a 'BCL meeting' [...] Heinz met these groups working under his inspiration and protection, he would speak to all of them [...]. He had the ability to understand [them all]. But it was not the case that everybody there was able to understand everybody [else] there. So he was the center of the BCL."[63] This "unbalanced" communication structure is also attested to by other sources, and can be confirmed by an analysis of the citations.

The end of the financial basis

The BCL could afford its idiosyncrasies and extravagances because its support came almost entirely from external sources—in particular from military organizations, as described above. But it was precisely this relative independence from local university structures, and the dependence on a trans-regional structure for promoting research that generously supported basic research at the BCL for over a decade, that finally led to the decline and the closing of the BCL. After 1969/70, the Mansfield Amendment permanently changed the conditions for the support of research.[64] New legislation now required that military financial support for research be limited to projects that actually produced results having direct military applications. No such projects were being pursued at the BCL.

Various attempts on Foerster's part to find substitutes for the now-unavailable funding, and to obtain more money for the BCL's basic research, failed in more or less dramatic fashion. Even projects that proposed application-centered research were refused. The BCL's final project, Cybernetics of Cybernetics, supported by the POINT Foundation, was both a successful attempt at codifying the epistemology that had been worked out at the lab and the establishment of a conceptual turning point: first-order cybernetics, concerned with "observed systems," was to be expanded and supplemented by second-order cybernetics, concerned with "observing systems." This added a new dimension to the idea of circular causality that had been the basic idea of the Macy conferences.

In mid-June 1974, Heinz von Foerster, recognizing the hopeless financial situation of the BCL, sought to retire from his professorship. Before the BCL was closed, its materials were archived and its instruments were offered to other laboratories. Two years later, the laboratory was fully "wound down," even for the doctoral students who had not yet completed their degrees. Foerster and his wife moved from Illinois to California. Today, the BCL building has been torn down.

In the last years before the closing of the BCL, Heinz von Foerster was able, in several important steps, to develop new contexts for, and new partial summarizations, of his work and the work of the BCL. Particularly noteworthy here are the linking of his work to that of Jean Piaget,[65] an extensive overview of cybernetic epistemology,[66] and a timely reformulation of the bionics research program.[67]

When I asked him about the problems that remained unsolved, Heinz von Foerster gave a very characteristic reply: the unsolved problems consisted above all in the lack of a final formulation of a theory of the unsolvability of problems.

A new beginning, and the transposition of the BCL research

With his retirement from his university professorship, Foerster began a new career that made it possible to direct the reception of his ideas, and thus those of the BCL, along entirely new paths. Via Gregory Bateson, whose 1972 Steps to an Ecology of Mind had found a broad readership,[68] Foerster entered the circle of the Mental Research Institute in Palo Alto,[69] where he now began to present lectures regularly. Ideas that had been developed in the context of the BCL, and had not been accepted by his peers there, now circulated among family therapists, and later among management and organizational consultants.[70] These could be seen as "applications" of the epistemology developed at the BCL, but beginning in the mid-1980s Foerster's still-developing epistemology began to gain in importance on its own. The Bielefeld sociologist Niklas Luhmann made a number of Foerster's ideas central to his own theory of social systems, including Foerster's theories of the observer, self-referentiality, and self-organization.[71] This led to a new, broader reception in the German-speaking world, extending far beyond the specialist boundaries of social-scientific systems theory. In this context, an older text of Foerster's on self-developing groups of constructivism was regarded as a basic reference.[72]

The end of the Biological Computer Laboratory was undoubtedly a delicate, difficult affair, and was a disappointment for its founder as well as for those who worked there. Besides the reasons adduced above for its end, it may also be worth considering whether Gerschenkron's theory of the competitive advantages of relative backwardness ought not to be complemented by a theory of the competitive disadvantages of relative progressiveness. The history of the BCL could provide an outstanding case study in support of such a theory.

Table 2: Sponsors of the BCL (1958-1974)[73]

1. Toward the Realization of Biological Computers. Contract NONR 1834(21), ONR Project No. NR 049-123; Sponsored by Information Systems Branch, Mathematical Science Division, Office of Naval Research. Period: 1 January 1958 to 31 July 1961. Principal Investigator: H. Von Foerster.
2. Mechanisms of White Cell Production and Turnover. United States Public Health Grant CA-04044; Sponsored by Department of Health, Education and Welfare, Public Health Service, National Institutes of Health. Period: 1 July 1958 to 21 October 1963. Principal Investigator: H. Von Foerster.
3. Analysis Principles in the Mammalian Auditory System. Contract No. AF 33 (616)-6428, Project No. 60(8-7232), Task No. 71782; Sponsored by Aeronautical Systems Division,Wright-Patterson Air Force Base, Ohio. Period: 1 May 1959 to 30 September 1961. Principal Investigator: H. Von Foerster.
4. Theory and Circuitry of Property Detector Nets and Fields. NSF Grant 17414; Sponsored by the National Science Foundation, Washington, D.C. Period: 27 March 1961 to 30 June 1962. Principal Investigator: H. Von Foerster.
5. Theory and Circuitry of Property Detector Nets and Fields. NSF Grant 25148; Sponsored by the National Science Foundation, Washington, D.C. Period: 1 July 1962 to 31 December 1963. Principal Investigator: H. Von Foerster.
6. Theory and Circuitry of Systems with Mind-Like Behavior. AF-OSR Grant 7-63; Sponsored by Air Force Office of Scientifc Research, United States Air Force, Washington, D.C. Period: 1 October 1962 to 31 October 1964. Principal Investigator: H. Von Foerster.
7. Semantic and Syntactic Properties of Many Valued Systems of Logic. AF-OSR Grant 8-63; Sponsored by Air Force Office of Scientifc Research, United States Air Force, Washington, D.C. Period: 2 October 1962 to 31 March 1964. Principal Investigator: Gotthard Günther.
8. Principles of Information Transfer in Living Systems. United States Public Health Grant GM-10718; Sponsored by Department of Health, Education and Welfare, Public Health Service, National Institutes of Health. Period: 1 May 1963 to 30 April 1966, Principal Investigator: H. Von Foerster; Co-investigator: W. R. Ashby.
9. Information Processing Capabilities of the University of Illinois Dynamic Signal Analyzer. Contract No. AF 33(657)-10659; sponsored by Aerospace Medical Research Laboratory, Air Force Systems Command, United States Air Force, Wright-Patterson Air Force Base, Ohio. Period: 1 February 1963 to 31 January 1964. Principal Investigator: M. L. Babcock.
10. Theory and Circuitry of Systems with Mind-Like Behavior. AF-OSR Grant 7-64; Sponsored by- Air Force Office of Scientifc Research, United States Air Force, Washington, D.C. Period: 1 November 1964 to 31 October 1965. Principal Investigator: H. Von Foerster.
11. Semantic and Syntactic Properties of Many-Valued and Morphogrammatic Systems of Logic. AF-OSR Grant 480-64; Sponsored by Air Force Office of Scientifc Research, United States Air Force, Washington, D.C, Period: 1. October 1963 to 30 September 1967, Principal Investigator: G. Günther.
12. Information Processing Capabilities of the University of Illinois Dynamic Signal Analyzer. Contract No. AF 33 (615)-2573; Sponsored by Aerospace Medical Research Laboratory, Air Force Systems Command, United States Ait Force, Wright-Patterson Air Force Base, Ohio. Period: 1 February 1965 to 31 January 1966. Principal Investigator: M. L. Babcock.
13. Cybernetics in Anthropology. Grant No. 1720; Sponsored by theWenner-Gren Foundation for Anthropological Research, New York, New York. Period: 1 February 1965 to 30 September 1966. Principal Investigator: H. Von Foerster.
14. Integration of Theory and Experiment Into a Unified Concept of Visual Perception, AF 49(638)-1680: Sponsored by The Air Force Office of Scientific Research, United States Air Force, Washington, D.C. Period: 1 March 1966 to 30 April 1969. Principal Investigator: H. Von Foerster.
15. Theory and Application of Computational Principles in Intelligent, Complex Systems. AF-OSR Grants 7-66 and 7-67; Sponsored by the Air Force Office of Scientific Research, United States Air Force, Washington, D.C. Period: 1 November 1965 to 31 October 1967. Principal Investigator: H. Von Foerster.
16. Cybernetics Research. Contract AF 33(615)-3890; Sponsored by Air Force Systems Engineering Group, Air Force Systems Command, United States Air Force, Wright-Patterson Air Force Base, Ohio, Period: 1 April 1966 to 31 March 1969. Principal Investigator: H. Von Foerster.
17. Information, Communication, Multi-Valued Logic and Meaning, AF-OSR 68-1391; Sponsored by Air Force Office of Scientific Research, United States Air Force, Washington, D.C. Period: 1 October 1967 to 30 September 1969. Principal Investigator: H. Von Foerster.
18. Study Toward the Mechanization of Cognitive Processes, NASA NGR 14-005-111; Sponsored by the National Aeronautics and Space Administration, Electronics Research Center, OZG 11.2000.1 29 Boston, Massachusetts. Period: 1 October 1967 to 30 September 1968. Principal Investigator: M. L. Babcock and H. Von Foerster.
19. Theory and Application of Computational Principles in Complex, Intelligent Systems. AFOSR Grant 7-67; Sponsored by the Air Force Office for Scientific Research, United States Air Force, Washington, D.C. Period: 1 September 1967 to 31 August 1969. Principal Investigator: H. Von Foerster.

20. Application of Cognitive Systems Theory to Man-Machine Systems. AF-OSR 70-1865. Sponsored by the Air Force Office of Scientific Research, United States Air Force,Washington, D.C. Period: 1 October 1969 to 31 September 1970. Principal Investigator: H. Von Foerster,
21. Notation of Movement. Grant DA-ARO-D-31-124-G998; Sponsored by the United States Army Research Office, Durham, North Carolina, Period: 1 March 1968 to 31 August 1969. Principal Investigator: H. Von Foerster.
22. Cognitive Memory, A Computer Oriented Epistemological Aproach to Information Storage and Retrieval. Grant OEC-1-7-071213-4557; Sponsored by the Office of Education, Bureau of Research, Washington, D.C. Period: 1 September 1967 to 31 August 1970. Principal Investigators: R. T. Chien and H. Von Foerster.
23. A Mathematical System for Decision Making Machines. AF-OSR 68-1391; Sponsored by the Air Force Office of Scientific Research, United States Air Force, Washington, D.C. Period: 1 October 1969 to 30 September 1970. Principal Investigator: G. Günther.
24. Toward Direct Access Intelligence Systems. AF-OSR Grant 70-1865; Sponsored by The Air Force Office of Scientific Research, United States Air Force, Washington, D.C. Period: 1 October 1970 to 30 September 1972. Principal Investigator: H. Von Foerster.
25. Cybernetics of cybernetics. Grant "Cybernetics of Cybernetics"; Sponsored by POINT, San Francisco, California. Period: 1 September 1973 to 31 August 1974. Principal Investigator: H. Von Foerster.

Footnotes

1 From an interview with Heinz von Foerster. The present essay would not have been possible without the energetic support, over several years, of Heinz von Foerster, who again and again patiently answered my questions (cited hereinafter as "interview with HvF"), and who made his archive (hereinafter "HvF archive") available to me. He has my warmest thanks. In addition, this work would not have been possible without the ongoing cooperation of Karl H. Müller, who shares my interest in the BCL and its founder.

2 A notable exception is to be found in Pierre Lévy, "Analyse de contenu des travaux du Biological Computer Laboratory (B.C.L.)," in: Ecole Polytechnique—CREA—Centre de Recherche Epistemologie et Autonomie, eds., Genealogies de l'auto-organisation, Paris 1985, 155-192; and Lévy, "Le théatre des opérations. Au sujet des travaux du B.C.L.," in: ibid., 193-224.

3 In relation to the present example: Stefano Franchi reports that at the University of Illinois, no one remembered the BCL only ten years after it closed. See Stefano Franchi, Güven Güzeldere, and Eric Minch, "Interview with Heinz von Foerster," in: Stanford Humanities Review 4 (1995), vol. 2, 288-307.

4 See e.g. Norbert Wiener, Kybernetik. Regelung und Nachrichtenübertragung im Lebewesen und in der Maschine, Düsseldorf et al., 1992 (orig. 1948).

5 W. Ross Ashby, An Introduction to Cybernetics, New York 1956.

6 A small attempt to rectify the situation has been made by Francisco Varela. See: Francisco Varela, "Heinz von Foerster, the scientist, the man," in: Stanford Humanities Review 4 (1995), vol. 2, 285-288.

7 An introduction to the biography of Heinz von Foerster, as well as a bibliography of his writings up to 1997, can be found in: Albert Müller, Karl H. Müller, and Friedrich Stadler, eds., Konstruktivismus und Kognitionswissenschaft. Kulturelle Wurzeln und Ergebnisse. Heinz von Foerster gewidmet, Vienna and New York, 1997. An overview of Foerster's work is found in: Heinz von Foerster, Sicht und Einsicht. Versuche zu einer operativen Erkenntnistheorie, Braunschweig, 1985; and in Foerster, ed., Wissen und Gewissen. Versuch einer Brücke, Frankfurt am Main, 1992; and in Foerster, ed., KybernEthik, Berlin, 1993; as well as in Foerster, ed., Observing Systems, Salinas 1981.

8 As far as is known today, Foerster did not produce any research results having direct or indirect military applications.

9 Heinz von Foerster studied at the Technische Hochschule Wien Technische Physik [Vienna Institute for Technical Physics]. Before finishing a degree there, he took on a job at a firm that made technical instruments for physics research. In 1944, he submitted a dissertation at the University of Breslau, and took the corresponding examinations. However, he was unable to produce the "Proof of Aryan Descent" that was required for the formal awarding of the degree, and so he did not receive his doctorate.

10 Heinz von Foerster, "Über das Leistungsproblem beim Klystron," in: Berichte der Lilienthal Gesellschaft für Luftfahrtforschung 155 (1943), 1-5. At the same time, he produced internal research reports on running projects, which were not published.

11 Heinz von Foerster, Das Gedächtnis: Eine quantenmechanische Untersuchung, Vienna, 1948. His first notes on preliminary studies for this book are contained in a manuscript notebook from 1945 (in the HvF archive).

12 The correspondence of the Deuticke-Verlag with the author in the years following the book's appearance attests to low sales figures (HvF archive).

13 Research on memory at the University of Vienna was pursued in accordance with entirely different concepts. See e.g. Hubert Rohracher, "Zur Physiologie des Gedächtnisses," in: Anzeiger der Phil.-Hist. Klasse der Österreichischen Akademie der Wissenschaften, 1948, no. 3, 41-55; see also Rohracher, Die Vorgänge im Gehirn und das geistige Leben, 2nd ed., Leipzig 1948.

14 Erwin Schrödinger to Hans Deuticke, 16 December 1948. Copy in the HvF archive.

15 On Warren McCulloch, see above all the Collected Works of Warren S. McCulloch, edited by Rook McCulloch, Salinas CA, 1989, four volumes, with numerous articles of commentary. More easily available is Rook McCulloch, Embodiments of Mind, Cambridge MA, 1965. For context, see Olaf Breidbach, Die Materialisierung des Ichs. Zur Geschichte der Hirnforschung im 19. und 20. Jahrhundert, Frankfurt am Main 1997, 367 ff.

16 Heinz von Foerster, "Quantum Mechanical Theory of Memory," in: Foerster, ed., Cybernetics. Circular, Causal, and Feedback Mechanisms in Biological and Social Systems. Transactions of the Sixth Conference, New York 1949, 112-145.

17 Steve Joshua Heims, Constructing a Social Science for Postwar America. The Cybernetics Group 1946-1953, Cambridge, MA and London, 1991. However, see also Jean-Pierre Dupuy, Aux origines des sciences cognitives, Paris 1994, and some references in Francisco J. Varela, Kognitionswissenschaft—Kognitionstechnik. Eine Skizze aktueller Perspektiven, Frankfurt am Main, 1990, 30 ff. A new interpretation can be found in N. Katherine Hayles, "Boundary Disputes. Homeostasis, Reflexivity, and the Foundations of Cybernetics," in: Configurations 2 (1994), 441-467.

18 Heinz von Foerster, ed., Transactions of the Sixth Conference, as in footnote 16 above; Foerster, Margaret Mead, and Hans Lukas Teuber, eds., Cybernetics: Transactions of the Seventh Conference, New York 1950; Foerster, Mead, and Teuber, eds., Cybernetics: Transactions of the Seventh Conference, New York 1950; Cybernetics: Transactions of the Eighth Conference, New York 1951; Foerster, Mead, and Teuber, eds., Cybernetics: Transactions of the Ninth Conference, New York 1953; Foerster, Mead, and Teuber, eds., Cybernetics: Transactions of the Tenth Conference, New York 1955. The transfer of the editorship to Foerster, the newest member of the group, was done partly in order to improve his competence in English.

19 According to the list of participants in the Transactions; as in footnote 18.

20 Interview with HvF.

21 See W. Ross Ashby, "Homeostasis," in: Foerster et al., Transactions of the Ninth Conference, as in footnote 18, 73-108, esp. 95: "Bigelow: It [Ashby's homeostasis] may be a beautiful replica of something, but heaven only knows what."

22 Manuscript in the HvF archive, titled "Phenomenology of External and Internal Work in the Active Whole Muscle," dated May 1957.

23 See Heinz von Foerster, "Metaphysics of an Experimental Epistemologist," in: Roberto Moreno-Diaz and José Mira-Mira, eds., Brain Process, Theories, and Models. An International Conference in Honor of W.S. McCulloch 25 Years after his Death, Cambridge and London, 1995, 3-10.

24 On the collaboration between Pask and Foerster, see also Heinz von Foerster, “On Gordon Pask,” in: Systems Research 10 (1993), no. 3, 35-42.

25 Gordon Pask and Heinz von Foerster, “A Predictive Model for Self-Organizing Systems,” in: Cybernetica 3 (1960), 258-300; Pask and Foerster, eds., “A Predictive Model for Self-Organizing Systems,” in: Cybernetica 4 (1961), 20-55.

26 See in general Rainer Paslack, Urgeschichte der Selbstorganisation. Zur Archäologie eines wissenschaftliches Paradigmas, Braunschweig 1991.

27 Marshall C. Yovits and Scott Cameron, eds., Self-Organizing Systems, New York, 1960.

28 Heinz von Foerster and George W. Zopf, Jr., eds., Principles of Self-Organization: The Illinois Symposium on Theory and Technology of Self-Organizing Systems, New York 1962.

29 See for example Ludwig von Bertalanffy, General Systems Theory: Foundations, Development, Applications, revised edition, New York, 1969.

30 See Heinz von Foerster, “On Self-Organizing Systems and Their Environments,” in: Yovits and Cameron, eds., Self-Organizing Systems, as in footnote 27, 31-50.

31 See the foreword to one of the first conferences in this area: “Heinz von Foerster, Bionics,” in: Bionics Symposium: Living Prototypes—the Key to New Technology, Technical Report 60-600, Wright Air Development Division, Ohio, 1960, 1-4; and Foerster, ed., “Bio-Logic,” in: Eugene E. Bernard and Morley A. Kare, eds., Biological Prototypes and Synthetic Systems, vol. 1, New York, 1962, 1-12. For a lexical overview, see Morley and Kare, eds., “Bionics,” in: McGraw-Hill Yearbook Science and Technology (1963), 148-151.

32 Heinz von Foerster, “Some Aspects in the Design of Biological Computers,” in: Second International Congress on Cybernetics, Namur 1960, 241-255.

33 See the pathbreaking article: Warren S. McCulloch and Walter H. Pitts, “A Logical Calculus of the Ideas Immanent in Nervous Activity,” in: Bulletin of Mathematical Biophysics 5 (1943), 115-133.

34 It is well known that this term was invented by John McCarthy.

35 George Brecher, Heinz von Foerster and Eugene P. Cronkite, “Produktion, Ausreifung und Lebensdauer der Leukozyten,” in: Herbert Braunsteiner, ed., Physiologie und Physiopathologie der weißen Blutzellen, Stuttgart 1959, 188-214; Brecher, Foerster, and Cronkite, eds., “Production, Differentiation and Lifespan of Leucocytes,” in: Herbert Braunsteiner, ed., The Physiology and Pathology of Leucocytes, New York 1962, 170-195.

36 See Heinz von Foerster, Patricia M. Mora and Lawrence W. Amiot, “Doomsday,” in: Science 133 (1961), 936-946; Foerster, Mora, and Amiot, “Population Density and Growth,” in: ibid., 1931-1937. Also, in general see: Heinz von Foerster, “Some Remarks on Changing Populations,” in: Frederick Stohlman Jr., ed., The Kinetics of Cellular Proliferation, New York 1959, 382-407.

37 See also Stuart A. Umpleby, “The Scientific Revolution in Demography,” in: Population and Environment. A Journal of Interdisciplinary Studies 11 (1990), 159-174.

38 See here Karl H. Müller, “Sozialwissenschaftliche Kreativität in der Ersten und in der Zweiten Republik,” in: ÖZG 7 (1996), 9-43, or Müller’s contribution to this volume.

39 See Heinz von Foerster, Der Anfang von Himmel und Erde hat keinen Namen. Eine Selbsterschaffung in 7 Tagen, ed. Albert Müller and Karl H. Müller, Vienna 1997, 213 ff.

40 See Marvin Minsky, Mentopolis, Stuttgart 1990. Maturana pointed out the difference between AI research and his own approach and that of the BCL in a very interesting manner: “The artificial intelligence researchers were imitating biological phenomena. If you imitate biological phenomena without distinguishing between the phenomenon and its description, then ultimately you are imitating the description of the phenomenon.” Volker Riegas and Christian Vetter, “Gespräch mit Humberto Maturana,” in: Riegas and Vetter, eds., Zur Biologie der Kognition, Frankfurt am Main 1990, 45.

41 Humberto Maturana, Biology of Cognition, Biological Computer Laboratory, Urbana, Illinois, 1970, (BCL Report 9.0). Maturana and Francisco Varela, Autopoietic Systems: A Characterization of the Living Organization. With an introduction by Stafford Beer, Urbana, Illinois, 1975 (BCL Report 9.4).

42 On the genesis of the term “autopoiesis,” see also Humberto Maturana, “The Origin of the Theory of Autopoietic Systems,” in: Hans Rudi Fischer, ed., Autopoiesis. Eine Theorie im Brennpunkt der Kritik, Heidelberg 1991, 121-124.

43 For an introduction and overview, see: Heinz von Foerster, ed., Cybernetics of Cybernetics, or the Control of Control and the Communication of Communication, 2nd ed., Minneapolis, 1995.

44 See Humberto Maturana, “Neurophysiology of Cognition,” in: Paul L. Garvin, ed., Cognition: A multiple view, New York and Washington 1970, 3-23, as well as Heinz von Foerster, “Thoughts and Notes on Cognition,” in: ibid., 25-48.

45 Interview with HvF, 26 November 1999.

46 Heinz von Foerster, “Proposal for a basic research program entitled: Toward direct access intelligence systems,” Urbana, 1 August 1970; Foerster, “Proposal for a basic research program entitled: Toward direct access intelligence systems,” Urbana, 1 June 1971.

47 Interview, 26 November 1999.

48 Paul Weston, “Proposal. Beyond numerical Computers: Technology for Information Processing in Higher-Order Representations,” Urbana, 1 June 1972. (Heinz von Foerster was an unnamed co-author of this proposal.)

49 Interview with HvF.

50 These excerpts from anonymous comments by experts are in the HvF archive.

51 Kenneth L. Wilson, The Collected Works of the Biological Computer Laboratory. Department of Electrical Engineering, University of Illinois, Peoria, 1976.

52 See e.g. Heinz von Foerster and James W. Beauchamp, eds., Music by Computers, New York et al., 1969.

53 See e.g. Peter Galison and David J. Stump, eds., The Disunity of Science. Boundaries, Contexts, and Power, Stanford, 1996.

54 Heinz von Foerster, “Computing in the Semantic Domain,” in: Annals of the New York Academy of Science 184 (1971), 239-241.

55 Heinz von Foerster, “Proposal for a study entitled ‘Theory and Application of Computational Principles in Biological Systems,’” Urbana, 1965.

56 Heinz von Foerster, “Proposal for a study entitled ‘Theory and Application of Computational Principles in Complex, Intelligent Systems,’” Urbana, 1966.

57 Heinz von Foerster, “Proposal for a study entitled ‘Toward the Mechanization of Cognitive Processes,’” Urbana, 1967.

58 Heinz von Foerster, “Circuitry of Clues of Platonic Ideation,” in: C. A. Muses, ed., Aspects of the Theory of Artificial Intelligence. The Proceedings of the First International Symposium on Biosimulation, Locarno, 1960, New York 1962, 43-82.

59 See Heinz von Foerster and Herbert Brun, “Heuristics. A Report on a Course in Knowledge Acquisition,” Urbana, 3 October 1970.

60 The model here was the Whole Earth Catalogue, for which Foerster wrote some articles.

61 The 1969 publication contained the results of a survey of its subscribers relating to their areas of competence and their scientific and personal interests. The 114 participants in the survey gave responses including “dope,” “LSD,” and “sex,” as well as “politics,” “beat the system,” “Vietnam,” and “finding Nirvana.” Of course, this can all be seen as a typical expression of the youth culture of the time.

62 See Foerster, Cybernetics of Cybernetics, as in footnote 43.

63 Interview with Humberto Maturana, 8 May 1998.

64 For the reference to the Mansfield Amendment, I would like to thank Stuart A. Umpleby, who was a student at the BCL (interview, 9 July 1998). On the effects of the Mansfield Amendment on the research environment in the US, see Bruce Spear, “Die Forschungsuniversität, der freie Markt und die Entdemokratisierung der höheren Bildung in den USA,” in: PROKLA. Zeitschrift für kritische Sozialwissenschaft 104 (1996). A representation that seems rather skewed towards the “victors”—“naturally” excluding the BCL Group—can be found in: Commission on Physical Sciences, Mathematics, and Applications, Funding a Revolution. Government Support for Computing Research, Washington, 1999.

65 See Heinz von Foerster, “Objects: Tokens for (Eigen-)Behaviors,” in: ASC Cybernetics Forum 8 (1976), 91-96, or Foerster, “Formalisation de Certains Aspects de l'Equilibration de Structures Cognitives,” in: B. Inhelder, R. Garcias and J. Voneche, eds., Epistémologie Génétique et Equilibration, Neuchatel 1977, 76-89.

66 Heinz von Foerster, “Kybernetik einer Erkenntnistheorie,” in: W. D. Keidel, W. Handler and M. Spring, eds., Kybernetik und Bionik, Munich 1974, 27-46.

67 Heinz von Foerster, “Notes on an Epistemology for Living Things,” BCL Report no. 9.3, Urbana 1972; Foerster, “Notes pour une épistémologie des objets vivants,” in: Edgar Morin and Massimo Piateli-Palmerini, eds., L'unité de l'homme, Paris, 1974, 401-417.

68 See Gregory Bateson, Steps to an Ecology of Mind. Collected Essays in Anthropology, Psychiatry, Evolution, and Epistemology, San Francisco 1972.

69 See Edmond Marc and Dominique Picard, Bateson, Watzlawick und die Schule von Palo Alto, Frankfurt am Main, 1991.

70 See Heinz von Foerster, “Principles of Self-Organization in a Socio-Managerial Context,” in: Hans Ulrich and Gilbert Probst, eds., Self-Organization and Management of Social Systems, Berlin, 1984, 2-24.

71 Niklas Luhmann, Soziale Systeme. Grundriß einer allgemeinen Theorie, Frankfurt am Main, 1984.

72 See Heinz von Foerster, “On Constructing a Reality,” in: Wolfgang F. E. Preiser, ed., Environmental Design Research, vol. 2, Stroudberg, 1973, 35-46.

73 Source: “Publications by the Members of the Biological Computer Laboratory,” B.C.L. Report No. 74.1, Champaign-Urbana, 1975, 3-6.

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