# Autopoiesis and Digital Design Theory: CAD Systems as Cognitive Instruments

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In contrast to traditional models of design process fundamentally defined by the abstract manipulation of objects, this study recognizes that the resources available for rethinking architecture are to be found in a reformulation of its theory and practice. This reformation should be based on non-linear design processes in which dynamic emergence and invention take the place of a linear design process fixed on a particular object evolution. Advances in computation thinking and technology have stimulated the design and formulation of a large number of design software. Its elaboration supposes a new conceptualization of our discipline's knowledge, in a body of principles and regulations, which commands the artifact's design and its realization; therefore, it constitutes a preliminary datum for its comprehension, and thereby is of theoretical importance. Despite the continuous increment of power in computers and software capacities, the creative space of freedom defined by them acting as cognitive instruments remains almost unexplored. Therefore, we propose a change from a design knowledge based on objects to one focused on design as a network of processes. In addition, this study explores the concept of Distributed Cognition in order to redefine the use of digital tools in design process as Cognitive Instruments.

### 1. Introduction

Advances in computational thinking and technology have stimulated the design and formulation of a large number of design software applications. Its elaboration anticipates a new conceptualization of architectural knowledge that frames and enables the elaboration of any architectural project. The conceptualization embedded in new CAD-based tools precedes the artifact's elaboration process; therefore, it constitutes a preliminary datum for its comprehension, and thereby is of theoretical importance. Despite the continuous increment of power in computers and software capacities, the creative space entailed by their capabilities remains almost unexplored. We define that space as the operational context of our proposed design process conceptualization.

## 2. Design as a process

Design may be defined in two different and commonly confusing ways. One definition regards the process of design or the design activity and the second views design through the product that has been designed. The following discussion concerns itself first and foremost with design as a process and emphasizes the misconceptions that come from studying products. We would like to argue that the core issue in design is establishing a process that builds internal insights and abstractions that are manifest in the tangible product. Although many have focused on the manifestation of design, in multiple cases the real purpose of design emerges as the internal insights and the discernment of an effective process. This is especially true if we think of design as an idiosyncratic process.

We propose a shift from a design knowledge based on objects to one focused on design as process. Design processes draw attention to topics as well as artifacts and pose questions about the ways they might be composed, or reformulated, analyzed and built. Through a sequence of iterative operations along the different stages of the design process – what we may call design history – artifacts are manipulated as spatial systems involving dimensions that may be thought of as movements, acts, and events. These spatial systems can be further analyzed in subsystems, through different operational conditions (technical, economical, functional, visual, morphological, geographical, etc.).

Furthermore, architectural design involves an ongoing negotiation or process between multiple actors (Client, Designer, Consultants, and Surveyors). These related aspects flow together into a conception-elaboration process through which the artifact emerges. Furthermore, the design process involves the transformation of concepts and into artifacts with a high level of physical complexity. Indeed, many of the parameters required to maintain coherence in the successful design process remain ignored even though they are implicit within the process itself. It is quite appropriate to think of the architectural design process as the continuous elaboration of research, a process of successive approximations in which the designer achieves numerous departures and returns between the different stages (iterative process). As we will suggest, articulation of epistemological conditions allow us to understand the design process as the progressive displacement from a theoretical body (abstract) into a physical object (concrete).

## 3. Design process models

As a result of an increasing demand for rational, predictive procedure within design practice, a host of design methodologies appeared during mid sixties [1]. In contrast to practices that appeared to many as neo-romantic appeals inspiration – really another version of black box models of design – there were multiple efforts to apply what was proclaimed to be a more scientific method that emphasized the rational and accessible but still omnipotent control of the designer. During the early seventies a second generation of methods appeared that often was often taken from problem solving methods or particularly, participatory problem solving methods [2]. In the past twenty years, computational models have been added to problem solving methods [3]. Based on the visual manipulation of a represented object, a process was defined that focused on response to a sequence of constraints. More recently, we find ourselves exploring cognitive models that seek to approach design problems not only from the vantage point of the objective but from an understanding of the shared cognitive setting in which they are produced.

Several of these cognitive models have essentially been derived from the analysis of the design process and from articulation of micro aspects that are often black boxed. For example, protocol analysis is the most used methodology of design process study. The analysis of design processes performed using protocols is based in two different approaches. The most common one refers to solving problem techniques developed by Simon and others. This model assumes an objective reality and describes design as an ill-defined problem in search of a rational solution. Constructivist interpretation offers a different strategy by approaching the problem as truly unique and requiring in inquiry not simply into "science in action" but "reflection in action".[4]

Even though we can detect a clear evolution in design process models, most of them can be grouped under a sequential process paradigm. Sequential models assume design process as a sequence of stages and understand the design process as linear. Here the process resembles what in science is viewed as a Newtonian or mechanistic model [5]. At this point we can clearly identify the ongoing influence of science in design that in the broadest sense extends all the way back to the scientific revolution [6]. However, if we are even more precise, we can notice a remarkable connection not simply between architecture and science but between architectural theory and the philosophy of science. This relation is carefully noted by Philip Steadman [6] and others [7–10]. For us, the main concern involves the active, dynamic relationship between science and architectural design. Rather than remaining fixed in obsolete models of science, design should give far more attention to research in the co-evolution of design in different fields. Indeed recent research [11, 12] – including our own – points towards a non-linear interpretation of design processes. Designers mentally construct their view of the situation as well as the actions taken within it [13]. From such a perspective, we would emphasize the shift from ontological categorization to the consideration of a phenomenology of design and cognitive articulation of design experience in order to uncover underlying structures that relates one design move to other or one design alternative to another. Such aspects have been sketched by others [2, 14–16], including Suwa and Tversky,stated to be who seemed to be interested in exploring the ways in which one phase of design establishes grounds for subsequent steps. Rather than considering the linkages between one "chunk" of design and another, we are interested in asking about the granularity of cognitive actions. By posing questions about patterns of design activities and relating them to instruments, we seek to develop design tools that may support non-linear routines within the design process.

## 4. Evolutionary design

Evolutionary design or generative design has constituted a leading edge in design research in the last decade. Its application comprises the use of several evolutionary computation or artificial intelligence techniques to generate design solutions [17]. Overall, methodology consists in the use of algorithms to increase and optimize the design-solution space. The approach – based on what is known as the neo Darwinist model – combines ideas from genetic theory from Mendel and evolutionary theory from Darwin to explain processes of natural evolution [18]. By using genetic algorithms and neural networks, evolutionary design integrates the idea of genetic coding with the definition of an artifact's structure. By importing ideas of selection and mutation, the process of studying generations of organisms becomes applicable to generations of architectural structure [18].

### 4.1 Genetic algorithms

Genetic algorithm introduced by John Holland in 1975[19] and initially applied to research related to natural and artificial systems is now applied in several other areas that primarily concern optimization of existing solutions. Genetic algorithms are applied to an initial population of individuals, each one including a genotype and a matching phenotype. Phenotypes are collections of parameters and genotypes are coded versions of the phenotypes. Each coded parameter is denominated by a gene. A collection of genes is a genotype and is usually represented as a string. In an evolutionary design process, artifact-genotypes combine to produce new versions that are then filtered through a fitness concept [20]. John Frazer's research group has done a remarkable body of architectural work using evolutionary computation [21].

### 4.2 Neural networks

Neural networks within architectural practice comprise collections of units that containing functions or simple processing elements that may be activated. For example, the replication of crowd movement through a defined space by using AI algorithms permit the definition of parameters that may be used to gauge the relation between total number of units representing people and crowd behavior. The technique imitates actual neuron ensembles and their behavior when activated. Design applications are derived from the fact that a particular design defines parameters that can then be tested [20].

### 4.3 Shape grammars

Shape grammar has been used to analyze and to describe designs, and to produce variations based on the same grammar [22]. A shape grammar consists of shapes, labels, shape rules, and an initial shape. Shapes and their labels are the basis for the definition of shape rules. Given an initial shape, one transforms it using the rules of the grammar to produce a new shape or shapes. Successive use of the grammar's rules on an initial shape produces designs. Shape grammars perform computations with shapes in two steps: detection of a particular shape and its possible substitute. Rules specify the particular shapes to be substituted and the manner in which they are replaced [23].

Underlying the rules are transformations that permit one shape to be part of another. Shape grammar and genetic algorithm fall under the same scientific paradigm. Both are methods that produce design's variations emulating natural evolution, as is understood under the neo Darwinist model also known as the old genetics paradigm [24].

## 5. Emergence in design

An interest in exploring the concept of emergence constitutes a significant explanation for the work in design evolution presented in the previous section. Emergence is a concept that describes unexpected discoveries, emergent phenomenon, or global behavior rising from the conjunction of local behavior or local conditions [25]. Drawn from artificial intelligence and biology theory, emergence describes non-deterministic, self-organizing phenomenon that arise from local interaction between low-level units within a system. In may cases, design interpretation, charged by questions that appear to be drawn from the setting of emergence shows that the concept is misunderstood or applied with limited understanding [11]. The design research community working with shape grammar, genetic algorithms, or their combination claims emergence as one of the most relevant advantages of using these techniques [26]. Even though, global patterns emerge from local conditions, there is really little that is useful here. Shape grammars generate shapes since the minimal unit is a shape, and genotypes recombine. Even though they are subject to mutation, they generate nothing but genotypes. What is of utmost importance is that the ways emergence has been incorporated by creative design calls attention to the limitations of linear, formalist models of design. Even more precisely, the artificial application of the concept of emergence to architecture, reminds us that a connection between design cognition and the organization of living systems is absolutely crucial. Rather than abandoning an idea of emergence, we would like to argue that instead of modeling emergence through linear genetic algorithms, we seek its force through a theory of self-organization. The following paragraphs sketch an argument that shows why a theory of self-organization should be of enormous relevance for understanding the design process.

## 6. Autopoiesis and architecture

The theory of Autopoiesis, proposed by Humberto Maturana and Francisco Varela in 1970 [27], argues that a living system embodies a continuous process of self-organization and emergence. According to Maturana and Varela, living systems are self-producing systems. In contrast to assumptions that viewed living systems as generators of something different from themselves, Autopoiesis approached systems as simultaneously producers and products [27]. Since an autopoietic system is organized as a network of processes of production that ultimately produce the system itself, they could claim that cognition was intimately linked to biological phenomena. Acting as a network of processes, the autopoietic system bears two distinct consequences. In the first, organization is understood as a network of production that makes the system possible; in the second, a particular structure constitutes a distinguishable component in the topology of the network [28]. Overall, organization determines the identity of a system, whereas structure determines how its parts are physically articulated. Organization identifies a system and corresponds to its general configuration. Structure shows the way parts interconnect.

According to Varela, we human being exist at the edge of the interaction between these two levels and he proposed an idea of the mind as an emergent and autonomous network of relationships saying "*la mente no esta en la cabeza*" -The mind is not in the head-, but extends throughout and even beyond body to encompass the world outside ourselves [29]. So human cognition emerges through self-organized processes that extent and interconnects the brain, body and environment in reciprocal loops of causation. In addition to the 'upwards' causation of personal consciousness by neural and somatic activity, there is the 'downwards' causation of neural and somatic activity by the person as an active, conscious agent [30].

### 6.1 Design process as an autopietic process

There are considerable implications of a design process approached from the vantage point of an autopoietic process. Given the limitations of previous evolutionary design process described above, we notice that Varela and Maturana provide grounds for approaching the constitution of design through cognition that is distributed or socially situated rather than dissecting the condition of one artifact in order to seek its replication through genetic code or grammar manipulation. It is through such a process that we may locate the emergence of novel design. It is precisely in such a way that we can understand the design process as fundamentally transformative and evolutionary process separate from the meta-stable replication of information.

### 6.2 Design process as emergence

The design research community has used the concept of emergence since the early nineties although with the limitations noted above. A more thorough analysis of the misconceptions that have accompanied emergence in architectural design and AI has been provided by Mary Lou Maher [11]. She has suggested not only that shape emergence was only part of a more completely realized theory of emergence in design but argued that it was also crucial to add behavior to structure in order to obtain a comprehensive theory. Drawing on Maher's analysis, we would argue that in order to seriously reengage the concept of emergence within the design process, it is essential to change our model from one strictly based on design objects and its behavior to one approaching design objects as indissoluble from the process that creates them, and inseparable from the process that fabricates them.

## 7. Design environments

Design environments constitute one fundamental concept in understanding an adequate taxonomy of design process. In fact, it is in the studio environment where students acquire knowledge and expertise that later are developed in practice. This becomes especially relevant in realizing the immense impact of digital technologies in traditional design settings. Rather than approaching architecture as a discursive evolutionary practice shaped through an intricate set of theories, methods and instruments, design thinking remains under what it is known as the cognitivist approach, i.e. the mind is in the brain. Unfortunately, this paradigm also remains the dominant scenario in architectural education [16]. It ignores possible interaction between the designer and the design environment in what we can denominate a phenomenology of design processes. Looking at the place of theories, methods and instruments, we would like to think of ourselves as engaged in a design process involving continuous materiality [31].

## 7.1 Theories, methods and instruments

Theories are general statements that make no reference to the specific problems or situations that they explain. Methods represent specific statements about action and organization of actions, generally based on a model or empiric knowledge [32]. Theories of design process are mostly based on two paradigms: (a) the cognitivist paradigm (i.e. problem-solving process) and (b) the constructivist (i.e. reflection in action) [2]. The former being the most popular in design research [2], mostly because the later has been not able to an adequate framework to describe how designer works. [33]

Furthermore, the way in which the memory-brain relation is interpreted in both models influence fundamentally the way in which design process is understood [34]. Both approaches assume "memory" and "thinking" as processes localized in the brain and based on internal representations.

In providing alternatives to the previous assumptions, we explore two alternative concepts coming from different areas of cognitive science. The first one is the concept of distributed or situated cognition [30] and the second one is considering memory as nonrepresentational [35]. Even though these concepts became important in reformulating a possible theory of design process, our attempt is explore the issue from the bottom up. Using concepts from the activity theory, we attempt to clarify the role of design instruments in design thinking. Activity theory was originated from the work of Lev Vygotsky [36] and declares that human interaction with the world is mediated by artifacts. In addition, post-cognitivist theoretical tradition in human computer interaction [37-40] will provide with effective conceptualization for our hypotheses.

## 7.2 Distributed cognition

The world in which we live is constituted by our perception, and it is our cognitive structure that enables us to have these perceptions. Therefore, our world is the world that we perceive. If the reality that we perceive depends on our structure, there are as many realities as individuals. Such a position explains why "purely objective knowledge" is impossible [41]. Since the observer cannot be separated from the phenomena he or she observes, we are determined by a cognitive biological structure in which the environment can only trigger alterations shaped by the structure of the organism itself [42]. Our perception of the world leads us to understand ourselves as separate from the world that we perceive. According to Maturana [43], since we live in the field of our vision, we do not see the space of the world. Since we live in our chromatic space, we do not see the colors of the world. If our perception constitutes only a portion of the whole, the same is true regarding our overall knowledge of the world. Maturana draws an even more challenging conclusion when he argues that higher human functions do not take place in the brain [44]. For Maturana, language, abstract thinking, love, devotion, reflection, rationality, altruism, are not features of human physiology or functions of the single body but social historical phenomena [45]. Instead of emphasizing the importance of objects, Varela proposed an additional emphasis on relations where an understanding of relations is indissoluble from process that constitutes the system [42]. Furthermore, here we can affirm that design products and the cognitive process of design are intimately connected and that to Varela, it is the network of interactions in its entirety that constitutes and specifies the characteristics of a particular cell, and not one of its components [43]. Distributed Cognition approach emphasizes the context-distributed nature of cognitive phenomena across individuals and instruments [39]. A main point of departure from the traditional cognitive science framework is that, at the "work setting" level of analysis, the distributed cognition approach explores how intelligent processes in human activity transcend the boundaries of the brain [46]. Consequently, instead of focusing on human activity in terms of mental processes acting upon internal representations, distributed cognition seeks to apply the same cognitive concepts to the interactions among a number of human actors and technological devices for a given activity [47].

## 8. Cognitive artifacts

The notion of Cognitive artifacts was introduced by Norman:

> "those artificial devices that maintain, display, or operate upon information in order to serve a representational function and that affect human cognitive performance." [48]

Cognitive artifacts are mental or physical devices that aid or enhance our cognitive abilities. This concept is quite interesting for design research; especially when realizing that design activities are highly mediated by many artifacts, i.e. drawings, methods, techniques, models, tools, instruments etc. In fact, in the last ten year an important portion of design research has been devoted to drawings and its use in design processes. [49–52]. This research has been mostly focused in what drawings represent, content rather than media i.e. how design is represented. The operational space in where these instruments operate remains mostly unknown. In exploring that space, activity theory from Vygotsky [36] opens an interesting area of research. In using activity theory, it is important to consider not only that designers interact with an artifact but also that they deal with an object of activity through the mediation of the instrument. In addition, designers adapt their activity to the artifact and they build new means and conditions for their future design activity [37].

## 8.1 Artifact–instrument relation

Our actions in the world are not direct, but mediated by socially and culturally constructed objects. These objects are artifacts, which are mediators of actions performed by an operator in pursuing activities [37, 38, 53, 54]. Socially and culturally loaded, they are shared and transmitted through communities in a continuous evolutive process. Artifacts already exist, but they need to be mobilized by users in performing activities to become instruments, i.e. means in the service of goal-oriented activity. Artifacts' appropriation through use situations transforms them into instruments. This process is defined as "instrumental genesis" and it is performed through "utilization schemes". This transformation process changes not only the organization of the activity (i.e."instrumentation") but also the artifact's characteristics and configuration (i.e."instrumentalization"). Using these ideas in design opens an interesting way to analyze design activities, especially when one thinks about drawings, drawing instruments and drawing techniques. In addition to that, the knowledge that they displace and the knowledge they produce are powerful for those analyses. Even though the use of drawings and its implications has been under theoretical discussion over time, [51, 55, 56], what has been also permanently ignored is the role of instruments in design thinking.

## 8.2 Utilization schemes

If artifacts are conceived as sets of negotiated, sedimented and embedded rules, their relevance in design thinking is extremely important and comprises many issues that until now remain ignored by design research. First, artifacts can be understood as means to improve design thinking, Second, artifacts can be also interpreted as a way to structure knowledge not only at organizational but also at operational level [57]. Reorganization of activity leads to the emergence of instrument "utilization schemes." [37, 40, 58] Using Piaget definition of scheme [59]; utilization schemes can be understood, as a structured set of generic descriptions of artifact utilization activities. They enable the subject to develop the activity necessary to perform the functions he expects from the association of the artifact with his action. They thus form a stable basis for his activity. The utilization schemes can be considered as representative and operative invariants, corresponding to classes of instrumented activity situations. But in a long-term perspective they evolves in the way that knowledge evolve. This is especially visible in the use of digital tools in architecture. At the origins of CAD use in architecture, utilization schemes were inherits from previous practices, i.e. electronic drafting tables. Later new utilization schemes were originated and implemented in newer CAD software versions. With the ubiquity of 3D modeling, totally new schemes were generated and are being absorbed, especially in academic environments [60, 61]. The same thing will happen with the availability of 3D prototyping. In the other hand, design processes stay unaltered and attached to old practices and obsolete paradigms.

### 8.3 Instrumental genesis

This approach is based on activity theory, which deals with purposeful interactions of active subjects with the objective world [53]. Interactions, or activities, are understood as social, hierarchically organized, developing, and mediated by artifacts. The instrumental approach focuses on integration of artifacts into the structure of human activities. The instrumental genesis approach, mainly developed by Bardel, maintains that genuine appropriation of artifacts by human beings is an outcome of developmental transformations of artifacts, individuals, and social interactions [40]. Not only do individuals change artifacts and adjust them for their specific needs and conditions, but they also become proficient in how to operate a tool, what tasks can be accomplished with the tool, and which methods should be applied to accomplish these tasks effectively. In other words, an artifact becomes an instrument through instrumental genesis [37].

## 9. Conclusions

Along this study, we redefine the use and concept of tool and material under the activity theory. Therefore, both tool and material can be understood as cognitive instruments within design activities. Although existing literature has covered issues about design instruments, those studies have focused on drawings and are concerned about what the designer is thinking when using them. This understanding is based on a notion of cognition that is becoming increasingly obsolete in the research community. Autopoiesis Theory from Maturana et.al, Activity Theory from Vygotsky, Distributed Cognition from Varela et al., and cognitive artifacts concept, are the foundation of this new research approach in understanding the role of artifacts as knowledge manipulation devices. What it is extremely relevant about their application to design theory is the original condition described at the beginning of this study, that is the split in design practice between information to describe objects and information about the realization or fabrication of those objects. Consequently, the final aim in design process should be to produce the necessary instruments not only to describe objects but also to fabricate them.

It is also fascinating to realize that design is an activity that produces knowledge instruments rather than physical objects. Objects are realized or fabricated out of these "knowledge instruments" through new instrumental genesis processes. There is something quite strange in the asymmetric relation between objects as knowledge driven instrumental genesis processes. For one, it brings into the discussion the concept of instrumental orchestration, that reminds us of a previous example in explaining emergence in design;

> "we would argue that in order to seriously reengage the concept of emergence within the design process, it is essential to change our model from one strictly based on objects and their behaviors to one based on approaching relations as indissoluble from the process that constitutes the system.
>
> For the purpose of clarification, let us consider the following example. Imagine that you are listening to a classical piece of music being performed by an orchestra in an auditorium. In what sense does the concept of emergence apply to the orchestra performance? We might immediately answer that what is being played and listened to constitutes an emergent phenomenon of the performance. But let's pose a second question as well. If the music is an emergent phenomenon, where does it emerge from? Or, what are the grounds of its emergence? If we approach the question from the design research community, we would answer that that the music emerges from the instruments and the score coordinated by a conductor. In other words, the music emerges under the direction of a self-contained script. The phenomenon we are describing, however, extends far beyond the consensual coordination of individual performances and involves our own perception." [31]

Finally, instrumental orchestrations could be reinterpreted using Trouche concept [64]: as the various devices that a designer organizes, with an aim of assisting the instrumental genesis in design processes.

The complexity of our orchestral example challenges us to extend our thinking about the design process as well. Rather than viewing emergence as the replication and enactment of a code, we should anticipate an evolutionary process that increases the quality and creativity. What we need as this point is an adequate model that will permit us to approach the design process as an autopoietic process.

In a subsequent analysis of evolving projects, the author will explore in further detail, ways in which one may integrate information acquired in the non-linear design process within the evolutionary model formulated by Varela and Maturana. In particular, in our future research, we will perform a series of protocol analyses focused on tracking design moves in relation to the use of instruments and their significance within design processes. This model will provide a conceptual framework for testing and developing a range of design tools. Desired improvements include capacity for better data structure manipulation and a graphic interface that will visualize the emergence of design and the understanding of the design process itself.

## Acknowledgements

I wish to thanks my PhD advisor Chuck Eastman for his constant intellectual support and guidance and to Kenneth Knoespel and John Peponis to share his thoughtful comments during the early phase of this study. In addition, this study has been partially supported by the College of Architecture at Georgia Institute of Technology, The Fulbright Commission and by the Chilean Government.

## References

1. De Vries, M., Cross, N., and Grant D., *Design methodology and relationships with science*, Kluwer Academic Publishers, Dordrecht; Boston,1993.
2. Dorst, K. and J. Dijkhuis, Comparing paradigms for describing design activity. *Design Studies*, 1995, 16(2), 261–274.
3. Liddament, T., The computationalist paradigm in design research. *Design Studies*, 1999, 20(1), 41–56.
4. Schon, D.a.W.G., Kinds of seeing and their functions in designing. *Design Studies*, 1992, 13(2), 135–156.
5. Saunders, P.T., Nonlinearity: What it is and Why it matters, in: Di Cristina, *AD: Architecture and science*, Wiley-Academy: Chichester, England, 2001, 110–115.
6. Steadman, P., *Evolution of Designs,* Cambridge University Press, Cambridge UK, 1979.
7. Pérez-Gómez, A., *Architecture and the crisis of modern science*. MIT Press, Cambridge, MA, 1983.
8. Galison, P. and Emily Thompson, *The Architecture of Science*. MIT Press, Cambridge, MA, 1999.
9. Di Cristina, G., *AD: Architecture and science*, Wiley-Academy ,Chichester, England, 2001.
10. Woolgar, M.L.A.S., *Representation in Scientific Practice*. MIT Press, Cambridge MA, 1990.
11. Poon, J. and M.L. Maher, Co-evolution and Emergence in Design. *Artificial Intelligence in Engineering*, 1997, 11(3), 319–327.
12. Dorst, K. and N. Cross, Creativity in the design process: co-evolution of problem-solution. *Design Studies*, 2001, 22(5), 425–437.
13. Winograd, T. and F. Flores, *Understanding Computers and Cognition: A New Foundation for Design*. Addison-Wesley Reading, MA, 1987.
14. Gero, J.S. and Hsien-Hui Tang, The differences between retrospective and concurrent protocols in revealing the process-oriented aspects of the design process. *Design Studies*, 2001, 22(3), 283–295.
15. Suwa, M., T. Purcell, and J. Gero, Macroscopic analysis of design processes based on a scheme for coding designers' cognitive actions. *Design Studies*, 1998, 19(4), 455–483.
16. Goldschmidt, G., Expert Knowledge or Creative Spark? Predicaments in Design Education, in: Cross, N. and Edmonds E. eds., *Expertise in Design: Design Thinking*

*Research Symposium 6*, Creativity and Cognition Studios, University of Technology, Sydney Australia.

17. Mitchell, M., *An introduction to genetic algorithms. Complex adaptive systems,* MIT Press, Cambridge, MA, 1996.
18. Frazer, J., *An Evolutionary Architecture.* AA Publications, London, 1995.
19. Holland, J., *Emergence: from chaos to order*, Addison-Wesley, Reading, MA, 1998.
20. Grierson, D.E.H. ed, *Emergent computing methods in engineering design: applications of genetic algorithms and neural networks*, Springer, Berlin; New York, 1996.
21. Frazer, J.F., Generative and Evolutionary Techniques for Building Envelope Design. in: Generative Art 2002.
22. Stiny, G., Introduction to shape and shape grammar. *Enviroment and Planning B*, 1980. 7, 343–351.
23. Stiny, G., Shape rules: closure, continuity and emergence. *Enviroment and Planning B*, 1994. 21, 1–29.
24. Ho, M.W., The New Age of the Organism, in: Di Cristina, *AD: Architecture and science*, Wiley-Academy: Chichester, England, 2001, 110–115.
25. Wilson, R.K., Frank C., *The MIT encyclopedia of the cognitive sciences*. MIT Press, Cambridge, MA, 1999.
26. Basil, S. and E. Edmonds, The cognitive basis of emergence: implications for design support. *Design Studies*, 1996, 17(4), 451–463.
27. Maturana, H.R.V., F.G., *Autopoiesis and Cognition*, Reidel, Dordrecht, 1980.
28. Thacker, E., *Biomedia*, University of Minnesota Press, Minneapolis, 2004.
29. Varela, F., *Conversaciones con Francisco Varela*, E. Goles, ed. 2000, Universidad de Chile: Paris. p. Interview.
30. Varela, F.J., Thompson E. and Rosch E., *Embodied Mind: Cognitive Science and Human Experience*. MIT Press, Cambridge MA, 2000.
31. Lyon, E. and K. Knoespel. Autopoiesis and Emergence in Architecture, in: *Conversations: Enacting New Synergies in Arts and Sciences*, Society for Literature and Science, Paris, France.
32. Smithers, T., On knowledge level theories of design process, in: Gero J. and Sudweeks F., eds *Artificial intelligence in design '96*, Kluwer Academic Publishers, Dordrecht; Boston, 39–57.
33. Dorst, K., Design, Science, and the Problems of Undetermined Problems, in: S. Culley, ed., *WDK; 28*, Professional Engineering for The Institution of Mechanical Engineers, Bury St. Edmunds, England. 775.
34. Schank, R.C., *Dynamic Memory: A Theory of Learning in Computers and People*. Univ. Press, Cambridge, UK, 1982.
35. Edelman, G. and Giulio Tonomi, *Universe of Consciousness: How Matter Becomes Imagination*. Basic Books, New York NY, 2000.
36. Vygotsky, L.S., *Mind in Society: Development of Higher Psychological Processes*. Harvard University Press, Cambridge, MA, 1978.
37. Rabardel, P. and G. Bourmauda, From computer to instrument system: a developmental perspective. *Interacting with Computers*, 2003. (15), 665-691.
38. Kaptelinin, V., Distribution of cognition between minds and artifacts: augmentation or mediation? *AI and Society*, 1996 10, 15–25.
39. Hutchins, E., *Cognition in the Wild*, MIT Press, Cambridge, MA, 1995.
40. Rabardel, P., *People and Technology*. 2002. in: http://ergoserv.psy.univ-paris8.fr [1-6-2005]

41. Maturana, H., Conversaciones con Humberto Maturana, E. Goles, ed. 2000, Universidad de Chile: Santiago Chile. Interview.

42. Maturana, H.R., Biology of language: Epistemology of reality, in: Lenneberg G.A.M.E., ed., Psychology and Biology of Language and Thought, Academic Press: New York, 1978.

43. Maturana, H.R.V., F.G., *The Tree of Knowledge*, New Science Library, Boston, 1987.

44. Varela, F.J., *Ethical Know-how: Action, Wisdom, and Cognition*, Stanford University Press, Stanford CA, 1999.

45. Maturana, H., The biological foundation of self consciousness and the physical domain of existence, in: Caianiello E.R., ed. *Physics of Cognitive Processes*, World Scientific, Singapore. 1987, p. 324-379.

46. Minsky, M.L., *The society of mind*, Simon and Schuster, New York, 1986.

47. Hollan, J., E. Hutchins, and D. Kirsh, Distributed Cognition: Toward a New Foundation for Human-Computer Interaction Research, Transactions on Computer-Human Interaction, 2000, 7(2), 174-196.

48. Norman, D., Cognitive artifacts, in: Carroll J., ed. Designing Interaction: Psychology at the Human-Computer Interface, Cambridge University Press, Cambridge, MA. p. 343, 1991.

49. Goldschmidt, G., The dialectics of sketching. *Creativity Research Journal*, 4 (2), 123-143.

50. Suwa, M. and B. Tversky, What do architects and students perceive in their design sketches? A protocol analysis, *Design Studies*, 1998, 18(4), 385-403.

51. Robbins, E., *Why architects draw*. 1994.

52. Do, E.Y.-L., *Right tool at the right time: investigation of freehand drawing as an interface to knowledge based design tools*, PhD Thesis in College of Architecture, Georgia Institute of Technology: Atlanta.

53. Leontiev, A.N., Activity, *Consciousness, and Personality*, Prentice-Hall, Englewood Cliffs, NJ., 1978.

54. Kaptelinin, V., Learning with artifacts: integrating technologies into activities, *Interacting with Computers*, 2003 (15), 831–836.

55. Perez-Gomez, A. and L. Pelletier, *Architectural Representation and the Perspective Hinge*, MIT Press, Cambridge MA, 1998.

56. Evans, R., *The Projective Cast: Architecture and Its Three Geometries*, MIT Press, Cambridge MA, 2000.

57. Masino, G. and Zamarianb M., Information technology artifacts as structuring devices in organizations: design, appropriation and use issues. *Interacting with Computers*, 2003, (15), 693–707.

58. Vérillon, P. and P. Rabardel, Cognition and Artifact: a contribution to the study of thought in relation to instrumented activity, *European Journal of Psychology in Education*, 9(3).

59. Piaget, J., *Biology and knowledge; an essay on the relations between organic regulations and cognitive processes*, University of Chicago Press, Chicago, 1971.

60. Kostof, S., *The Architect. Chapters in the History of the Profession*. University of California Press, Berkeley and Los Angeles, 2000.

61. Allen, S., *Practice: architecture, technique and representation*. G+B Arts International, Amsterdam, 2000.

62. Hambly, M., *Drawing instruments*, Philip Publishers, London, 1988.

63. Mitchell, W.J.M. and M. McCullough., *Digital design media*. Van Nostrand Reinhold, New York, 1994.

64. Rouche, L., From artifact to instrument: mathematics teaching mediated by symbolic calculators, *Interacting with Computers*, 2003 (15), 783–800.

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