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THE BIRTH AND HISTORICAL DEVELOPMENT OF COMPUTATIONAL INTELLIGENCE APPLICATIONS IN ARCHAEOLOGY

1. Introduction

Is it possible to build a machine to do archaeology? Will this machine be capable of acting like a scientist? Will this machine be capable of understanding how humans act, or how humans think they acted in the Past? These questions are rather original in Archaeology. They are even provocative, given the current fashion of post-modern and hermeneutic approaches. Nevertheless, the dream of an automated archaeology has existed latently in some hidden places of the archaeology.

The so called "intelligent" machines incite instinctive fear and anger by resembling ancestral threats – a rival for our social position as more or less respected specialists. But robots are here, around us. So, why should we fear a machine classifying a prehistoric tool and deciding "intelligently" its origin, function and/or chronology?

The debate is between what is considered an *artificial* way of reasoning (computer programs) and a *natural* way of reasoning (verbal narrative). Critics of computationalism insist that we should not confound scientific statements with predicate logic operations, since discursive practices or argumentations observed in a scientific text are not "formal". By that reason, they are tributary, to a certain extent, from the Natural Language and the narrative structure (literary) of which scientific texts derive. Personally, I take the opposite approach: scientific problem solving stems from the acquisition of knowledge from a specific environment, the manipulation of such knowledge, and the intervention in the real world with the manipulated knowledge. The more exhaustive and better structured the knowledge base, the more it emulates a Scientific Theory and therefore the easier the solution is to the scientific problem, the more adequate the interpretations we will get.

As its history proves, computational intelligence is not just about robots. It is also about understanding the nature of intelligent thought and action using computers as experimental devices. In the following pages I will consider whether this is also a possible "metaphor" to understand the way archaeologists think.

2. Machines who think

The dream of an "intelligent" machine is very old in the history of Philosophy, and it is related to the progressive discovery that nature and human acts are not divine secrets, but could be broken down and understood systematically. Since Socrates, philosophers have often anthropomorphized a problem by imagining a *demon* accomplishing a task that was difficult to understand but seemed to be possible. In some cases, such a demon had a kind of mechanical nature. Maybe the most relevant "precedent" of computational intelligence was the logic imagined by Ramon Lull, a medieval mystic (13th. century), and one of Catalonia's greatest poets. More than three centuries after the *Ars Magna* this book influenced Thomas Hobbes (1588-1679), who stated «by ratiocination, I mean computation. Now to compute is either to collect the sum of many things that are added, or to know what remains when one thing is taken out of another. Ratiocination, therefore, is the same with addition and subtraction». Hobbes wanted to account for all cognitive activities of the mind in terms of computation, and computation is calculated in terms of manipulation (transformation) of computable entities.

Gottfried Wilhelm von Leibniz (1765) envisioned a universal calculus of reasoning by which arguments could be decided mechanically. «Everything proceeds mathematically...if someone could have a sufficient insight into the inner parts of things, and in addition had remembrance and intelligence enough to consider all the circumstances and take them into account, he would be a prophet and see the future in the present as in a mirror». He seemed to see the possibility of mechanical reasoning devices using rules of logic to settle disputes.

Many of the natural philosophers of the Enlightenment took similar views. Julien Offray de La Mettrie (1709-1751) was perhaps the first to suggest that "man is a machine", more as a metaphor than as a mechanical possibility. We had to wait until 20th century for a new turn of the screw. In 1914, Bertrand Russell imagined recording instruments that could perceive the world in place of a human observer. Russell's virtual observer eliminates the subjectivity of perception of what things really are. «There is no theoretical limit to what can be done to make mechanical records analogous to what a person would perceive if he were similarly situated» (Russell 1959).

With early twentieth century inventions in electronics and the post–World War II rise of modern computers, possibilities gave over to demonstrations. As a result of their awesome calculating power, computers in the 1940s were frequently referred to as "giant brains". As a consequence, in the middle of the 20th century, a handful of scientists began to explore a new approach to thinking machines based on their discoveries in neurology, a new mathematical theory of information, the engineering approach to control and stability mechanisms, and the availability of machines based on the abstract essence of mathematical reasoning.

The first computer systems displaying cognitive capacities considered "intelligent" (language understanding, learning, reasoning, problem solving) were presented in 1956, at the Dartmouth Conference. At the same time, John McCarthy coined the term *Artificial Intelligence*. McCarthy's main assumptions were that if a machine can do a job, then an automatic calculator can be programmed to simulate the machine. Knowledge was viewed as something that could be stored, coded, matched, and displayed. An artificial brain could be built simply by telling it what it needs to know. It was hoped that if we could represent the knowledge necessary to describe the world and the possible actions in a suitable formalism, then by coupling this world description with a powerful inference machine one could construct an artificial agent capable of planning and problem solving.

The turning point came with the development of knowledge-based systems in the 1960s and early 1970s. It has been explained as a "paradigm shift" in computational intelligence toward knowledge-based systems. The thousands of knowledge-based mechanisms or "expert systems" following it became visible demonstrations of the power of small amounts of knowledge to enable intelligent decision-making programs in numerous areas of importance. Although limited in scope, in part because of the effort to accumulate the requisite knowledge, their success in providing expert-level assistance reinforces the old adage that knowledge is power. But it was this advantage which at the end acted as their main handicap. Artificial Intelligence began to lose its holistic character towards a general theory of intelligence, acquiring a more "application" orientation. Knowledge-based systems were useful tools, although they do not simulate how humans think.

About the same time, computer specialists began to realize that scientific reasoning can be described in terms of problem solving search (Langley *et al*. 1987; Thagard 1988; Wagman 2000). According to that view, scientific theories may be considered as complex data structures in a computational system; they consist of highly organized packages of rules, concepts, and problem solutions. The idea is that scientific knowledge directs problem solving search through a space of theoretical concepts. This specific knowledge matches against different possible regularities in the data and take different actions depending on the kind of regularity the system has perceived among external data. Some of this knowledge proposes laws or hypotheses, others define a new theoretical term, and yet others alter the proposed scope of a law. Different data led to the application of alternative sequences of knowledge operators, and thus to different conclusions.

Generating a scientific explanation would be then a type of problem solving search, in which the initial state consists of some knowledge about a domain, and the goal state is a hypothesis that can account for some or all of that knowledge in a more concise form. A space of instances and a space of hypotheses should then be used, with the search in one space guided by information available in the other. That is to say, the use of instances constrains the search for hypothetical statements of the causal relationship. Hypotheses are evaluated through known instances of the causal relationship. In looking for appropriate instances of examples, scientists are faced with a problem solving task paralleling their search for hypotheses. They must be able to plan by making predictions about which observational (or experimental) results could support or reject various hypotheses.

If a computer program could be developed to *do* what we usually call “science”, then an intelligent robot able to substitute us in the tedious task of studying ourselves should also be possible. In 1965, Herbert Simon predicted that machines would be capable of doing any work a man could do by 1985. When that date arrived, and the promised intelligent machines were still not available, a critical approach to the very idea of thinking machines began. This failure precipitated the separation and rivalry of the two founding disciplines: Cybernetics and Artificial Intelligence. Cybernetics fundamental ambition was to produce a physically touchable theory of that most unphysical entity: the mind itself. The cybernetics researchers began their investigation of nervous systems by creating automata creatures reproducing what we (animals) can *do*. The artificial intelligence community ignored this approach in their early work and instead set the sights directly on the “intellectual” side of human thought, in experiments running on large stationary computers dedicated to the mechanizing of pure reasoning.

3. Archaeological reasoning as computation

The first requisite for an automated archaeology should be based on the dream of Hobbes, “rationalization as computation”. Formal logics, mathematics and computers have been used in archaeology, but the vast majority of their archaeological applications pertain to the domain of methodology or, even worse, to the design of data collections. In many cases, such efforts were not directed to the examination of the structures of archaeological reasoning and argumentation.

Although computers and statistics began to be used in archaeology in the 1950s, we had to wait until the end of the 1960s, when “new archaeologists” began to explore Hobbes argument. In so doing they emphasized the need to make disciplinary assumptions formal and explicit. Such authors considered that computer methodology provided an expanding armory of analog and digital techniques for computation, experimentation, simulation, visual display and graphic analysis. In that sense, it fulfilled a second requirement for automated archaeology: Russell’s challenge for eliminating the subjectivity of perception and explanation in terms of some kind of externalized *demon*. Mathematical techniques, as sense-extending machine tools could either be used like the microscope to examine the fine structure of low-level entities and processes in minute detail, or like the telescope to scrutinize massive ensembles over vast scales. They also seemed to provide powerful hammer-and-anvil procedures to beat out archaeological theory from intransigent data; thus, on one hand these methods can be used to construct models and simulate their consequences over a range of states, identifying test-conditions; on the other hand, the computer may be used to analyze and test real data and measure their expectations under the model against the reality.

Doran and Hodson (1975, 74, see also Doran 1970) already suggested that the question "Can a computer do this?" is almost always rephrased as "Can this procedure exactly be specified?". In his book, *Analytical Archaeology* (Clarke 1968, 512-513) David Clarke noted three ways to explore rationalization as computation in archaeology:

1. using descriptive statistics for concept definition and quantification;
2. using analytical inductive statistics to handle relationship concepts;
3. using isomorphic systems of symbols arranged in axiomatic schemes, models or calculi to handle the regularities in complex data.

The main problem in those years was that many scholars regarded mathematics and statistics as an analytical tool to be "used", and not as a way to transform rationalization into computation. Only some limited aspects of archaeological reasoning were computationally formalized, like classification and seriation. Some emphasis was placed on statistical hypothesis testing, but there was very poor application of mathematical formalism to the theoretical issues of archaeology, despite recognition of the value of axiomatically or formally expressed theory (Read 1990). The naive use of Hempelian hypothetico-deductive reasoning mechanism as a "method" to test hypotheses is a good example. Statistics was placed at some part of the reasoning cycle, leaving the rest of the explanatory process in traditional narrative terms. A cautious note by Doran and Hodson (1975), the founding fathers of quantitative archaeology, is very interesting in this regard. They found the claims for a "formalized" approach to archaeology greatly exaggerated and therefore dangerous. While they share some of the dissatisfaction with subjectivities in archaeological explanation at that time, the proposed solution – the hypothetical-deductive method – was considered as a bizarre mixture of naivety and dogmatism. Formalization was still regarded as an "alien" conception.

A similar theme was iterated by Cowgill (1986, 369) in a review article titled *Archaeological Applications of Mathematical and Formal Methods*. There he referred to three broad categories comprised of «archaeological observations, analytical methods, and sociocultural theory», but then observed that although some anthropological reasoning was expressed directly in computational (mathematical) terms, most of it was still expressed in a subjective narrative way.

The first synthetic models of archaeological inference were proposed by D. Clarke (1972), M.B. Schiffer (1976), M. Borillo (1977), among others. They argued for the formalization of the acquisition of archaeological knowledge in terms of sets of laws, correlates and cultural and natural transformation processes. The cybernetic theory of the 50s and 60s provided the language necessary for that formalization. Instead of considering "archaeology" as a machine, "new archaeologists" regarded human society, and even the human individual (but not the archaeologist!) as a machine, forming a complex whole or "system". Here, "machines", "automata", and "societies" were synonymous. Archaeologists were convinced that they should study the relationships between "components" to discover how the system worked in the past. The links between elements or subsystems were examined in terms of *correlational structure* (Clarke 1968).

Only in the mid-1980s, a step forward towards a full formalization was made, when archaeologists realized the need to impose a concordance between the language of the model, the assumptions of the model and its interpretability (Carr 1985; Read 1985). The problem arising with axiomatization was not whether archaeologists have developed a theory that can be recast in axiomatic fashion but whether there are principles or relationships suitable for restatement as axioms for an axiomatic construction. The real fact is that archaeologists do not know exactly what archaeology is.

4. Simulating archaeologists

Jean-Claude Gardin became a professional archaeologist by chance at the end of the 1950s, and consequently he always had an outsider's view of what archaeologists do. Instead of a normativist approach to archaeology, suggesting the best way of *constructing* the archaeology we need, he took an analytic point of view, looking for ways of *deconstructing* what archaeologists *believe they do*. His purpose was to expose the logical flaws in argumentation and so to improve the logical execution of reasoning. This would allow the study of archaeological logic itself.

According to Gardin, the concrete expression of reasoning in any dominion of science is the text where the author has expressed the mental operations that have led him/her from the observation of certain empirical facts, to the affirmation of certain explanatory proposals. This methodology looks for the necessary bridges between facts and theses and the links between explanations. It has been called *logicist analysis* (Gardin *et al.* 1981). Its goal is to reduce the content of the text in its main components, studying their fundamental connections. The schematization of an archaeological paper is not an abstract or a summary of the paper, but a reformulation of its content in a condensed form. Gardin uses the word "condensation" as in physics: a rearrangement of something into a more compact volume, without loss of substance. He and his colleagues "have deconstructed" numerous scientific works (mainly archaeological) in this way. This approach is precisely a framework for analyzing and modeling the questions and answers that bracket a scientific text, and there is an obvious intuitive link between meaning, questions, and answers.

Gardin assumed that our theoretical constructs can be expressed in terms of a "calculus". Archaeological theories can be formulated as computational structures with two components. The first one is a *facts base*, here understood as a set of declarative propositions that include not only descriptions of archaeological materials and their context, with associated archaeometric data, but also a large number of referential statements. Those statements are not usually regarded as "data"; they include primarily vast sets of analogies, "common sense", shared belief, ideologies, etc. The second component is an inferential tree made up of rewrite operations, which reproduce the chain of inferences from the archaeological record ("facts", represented as P_o) to different explanatory statements (P_n). Between the extremes of the argumentation, there are intermediate theses (*Pi*). Scientific reasoning builds chains of oriented propositions P_o, P_1, P_2..., P_n in terms of successive operations P_i --> $P_{i+1.}$ (Gardin 1980, 1991, 1993, 1994, 1998, 2003).

"Rules" are the key; not laws, which are inviolate, but rules that can be changed and indeed are always changing in a reflexive relationship allowing the expert (human or machine) to accommodate new information. Given some empirical data (observations) about a particular archaeological case, and some bit of associative knowledge (If…Then) (hypotheses and interpretations considered valid in a Social, Anthropological or Historical Theory), the archaeological problem can be explained in terms of the knowledge stored in a series of rules. In other words, given some visual input and a candidate explanatory causal model, a correspondence can be established between them. This means that a small number of features are identified as matching features in the input and the model. Based on the corresponding features, a decision rule linking visual features with their causal process (social activity) is uniquely determined. The recovered decision rule is then applied to the model. Based on the degree of match, the candidate causal event is selected or rejected. To be accepted, the match must be sufficiently close, and better than that of competing solutions.

The rules discovered by logicist analysis may be subjective, but they are explicit. Anyone can produce the same results, so that although the system is subjective, it will be consistent when different subjectivities (i.e. different individuals) use it. The acceptance of the assumptions on which the problem solution is based leads to consistency, and direct comparability between results produced by different people; this fulfills the basic requirements of objective data within the consensus reality of mutual users of the program. Therefore, logicist analysis can extract objective-like knowledge, but the complexity of the dynamic process is retained and the data is produced in the form of probabilities that can be compared as if they are objective data within a defined consensus reality.

Analogies between logicist analysis and some aspects of artificial intelligence are patent, although both representation schemas evolved in parallel without further implications (Gardin 1980, 123-125, 1991; Gardin *et al.* 1987). Formal characteristics of Expert Systems technology appear to be very similar to the general structure of logicist analysis rewrite rules. The "deconstruction" of a scientific text in terms of rewriting operations agrees with the "extraction" of the expert knowledge in terms of production rules. In the same way that the knowledge engineer tries to find out how a human expert thinks before introducing "prior knowledge" into the computer program, the logicist analyst tries to study what is hidden inside a scientific text written in natural language.

Gardin accepted that the way archaeologists make decisions can be mechanized. Although he never tried to build an automated archaeologist, his suggestions moved some archaeologists to create what at first look seem to be "automated archaeologists". The most obvious application of this "automatization" of archaeological reasoning is the domain of archaeological typologies. In the same way, the function and chronology of ancient buildings can be correctly explained from their observed architectural features, and the visual characteristics of human and animal bones can be used to recognize them as instances of well defined explanatory categories. It is also possible to mechanize the process of microscope samples classification for ancient wood taxonomy determination. Some other systems help scientist to decode decorative patterns in pottery or rock-art. Other archaeological applications have explored the possibilities of whole artifact identification from the perception of sherds. Applications of automated problem solving methods do not finish here. An expert system can be programmed to help archaeologists to interpret the results of archaeometric analyses, within the framework of provenance studies. Such a system would produce one (or several) "diagnoses" according to the geographic origin of raw material, from a database of analyzed samples of known origin provided by the user (see a review of such applications in Barceló 2008).

5. What computers could not do years ago and what they can do now

Herbert Simon's prediction that machines would be capable of doing any work a human can do by 1985 was soon considered over-optimistic by some authors, exaggerated for others, or even wrong for many computer scientists and philosophers. Some years before that landmark date, it became clear that intelligent machines could not be produced. In fact, even today, 25 years after the deadline, we still have not arrived at a true computational intelligence. In the same way, and around the same years GIBBON (1984, 383), though espousing the value of formal and axiomatically expressed theory in archaeological reasoning, bluntly commented that «no theory within archaeology has ever been formalized». The impossibilities of machine intelligence and automated archaeology seem to have been detected simultaneously: there is no easy way to translate rationalization into computation.

In any case, we have to accept that the very idea of "rationalization as computation" never found the place in archaeology (nor in any other social science) it merited. The most promising computational techniques in those early days were accused of excessive simplification, of forcing knowledge, or distorting it, and of failing to exploit fully the knowledge of the expert (HUGGET, BAKER 1986; WILCOCK 1986; DORAN 1988; GALLAY 1989; LAGRANGE 1989; SHENNAN, STUTT 1989; FRANCFORT 1990; PUYOL-GRUART 1999).

However, there is nothing suspicious in the approach. The success of expert systems in parallel disciplines is very evident if we consider the thousands of references, and it is due to their working within a world in which the range of meaning for terms is circumscribed within a carefully selected micro-world. Yes, they may not be a model of human reasoning, as considered by Gardin, but this technology really works! The problem is that archaeology has not yet arrived at a relevant degree of formalization, given absurd prejudices and the weight of individual authority. Robots are not the guilty ones, but the humans that have not learned how to program them!

In archaeology, the so called "radical critique" of the 1980s distorted the debate when it regarded archaeology as literature. There are still scholars considering that any archaeological analysis is a mere text product of an individual writer. Consequently the explanation of past behavior has the same value as a literary product. Even the practice of archaeology can itself be reduced to "theatre". Given that robots can not act, there are no automated archaeologists! Given that rationalization is seen as art (literature), it is believed that it cannot be rendered computable, because the act of literary creation is intrinsically incomputable.

The question never arrived at this extreme in the Artificial Intelligence debate. Although by 1985, computer scientist and cognitive psychologists were well aware that no general theory of rationalization could be rendered computable, and no "artificial human brain" has ever been programmed, they had already proved that intelligence could be mechanized in very restricted domains. Within the last two decades, the view of computational intelligence based on pre-set plans and searching in restricted knowledge-bases using well-defined operators for activating already existing sequences of explanations (i.e. expert systems) has come under scrutiny from both philosophers and computer scientists.

The main consequence of this profound criticism was the revival of the cybernetic approach in the late 1980s, and its integration with new paradigms of cognitive science, philosophy and a so called "new" artificial intelligent paradigm. A shift in perspective from *knowledge as stored artifact* to knowledge as *constructed capability-in-action* inspired a new generation of cyberneticists in the fields of situated robotics (Brooks 1999; Franklin 1995; Clancey 1997; Pfeiffer, Scheier 1999; Iyida *et al.* 2004). To be intelligent, an intelligent machine should focus on the outside world, how this world constrains and guides its explanatory behavior. The automated system we would like to build is the agent-in-the-right-context, an agent constructing descriptions by adapting old ways of perceiving, by putting models out into the world as artifacts to manipulate and rearrange, and by perceiving generated descriptions over time, relating them to past experiences or future consequences.

Machine Learning appears then as the key word in the New Cybernetics. That is to say, we do not simply ask: "What knowledge structures should be placed on the head of a robot able to do archaeology?". Instead of storing declarative sentences in the computer's memory, we should build a machine able to *learn* from its own explanations and mistakes. If we want to go beyond the traditional expert-system approach, we should make emphasis not on database consultation, analogy, and simple statistical decision-making, but on learning and categorizing, and on how meaning can be generalized from known examples of a given concept. Fortunately, learning is not an impossible task for computers. New generation adaptive algorithms (neural networks, support vector machines, genetic algorithms) appear to be formally true universal inductive algorithms, and they can be used to solve many archaeological problems (Barceló 2008).

Programming computers to be able to solve most learning problems is a cross between statistics and computer science. The idea is to program a system able to look for common features between positive examples of an observed or simulated causal relationship to be predicted, and common differences between its negative examples. In contrast with discrete Aristotelian logics, machine learning models provide more *graded* answers to archaeological problems. Such programs integrate information from a large number of different input sources, producing a continuous, real valued number that represents something like the relative *strength* of these inputs. These graded signals can convey something like the *probability* of the answer or explanation in some specifically constrained circumstances.

Computer scientists are intensively exploring this subject and there are many new mechanisms and technologies for knowledge expansion through iterative and recursive revision. Artificial Intelligence offers us powerful methods and techniques to bring about this new task. Fuzzy logic, rough sets, genetic algorithms, neural networks, Bayesian models and agent-based systems are among the directions we have to explore. These paradigms differ from usual methods in that they are (in comparison at least) robust in the presence of noise, flexible as to the statistical types that can be combined, able to work with feature (attribute) spaces of very high dimensionality, they can be based on non-linear and non monotonic assumptions, they require less training data, and make fewer prior assumptions about data distributions and model parameters. The huge number of learning algorithms and data mining tools make it impossible to review the entire field in a single paper (Jones 2007; Luger 2008; Munakata 2008; Hassanien *et al.* 2009; Bar-Cohen *et al.* 2009).

No aspect of this discussion has entered into the archaeological debates of our time. Critics of the "rationalization as computation" view of archaeological discipline are ignorant of this revival of the cybernetic paradigm, and its integration with new paradigms of cognitive science, philosophy and new programming approaches. What at the beginning seemed correct criticisms of the view of human society as a *simple* machine, soon became an hysterical rejection of formalization and any possible surrogates: computers, statistics and formal logics. The idea of "art" or "humanities" has been violently vindicated favoring explanation via "common sense", ignoring the fact that artificial intelligence is technologically achievable provided we change the classical approach of its early days: if we want to reproduce human intelligence in a machine, we should make emphasis on three central aspects: development, interaction, and integration. Development forms the framework by which machines should imitate the way humans successfully acquire increasingly more complex skills and competencies. Interaction should allow robots to use the world itself as a tool for organizing and manipulating knowledge, it allows them to exploit humans for assistance, teaching, and knowledge. Integration should permit an automated archaeologist to maximize the efficacy and accuracy of complementary mechanisms for perceiving and acting.

Therefore, what would give a more "intelligent" character to automata applications in the archaeological domain will not be a passive storing of individual rules, but an enhanced ability to learn and to react in a certain way to a certain stimulus. If we want to go beyond the usual archaeological explanations based on template matching, we should place emphasis not on database consultation, analogy, and decision-making, but on learning and categorizing, and on how meaning can be generalized from known examples of a given concept. That is, the automated archaeologist should develop its own cognitive machinery (what it knows) as opposed to construct a data structure on which a preexisting machinery operates.

6. Conclusions

The failure of the early prospect of Artificial Intelligence was attributed to a view of intelligence as an abstract machine. In the same way, the failure of the New Archaeology of the 60s was its insistence on simple universal theories of human behavior. The reaction should be based on a move towards a view of knowledge as something created from transformations of previous knowledge. Information does not exist in the world waiting to be extracted by a robot, but, rather, it should be situated in meaningful contexts. Perceiving a world implies distinguishing "possibilities for action" and not naming or identifying *per se*. Explanation cannot be properly understood, if considered independently of the context in which it occurs. The historical, cultural, and social context of the interactions of an intelligent machine is crucial to the understanding of the ongoing process. That is to say, the archaeological record is here defined in terms of the recognition of the circumstances to act with or upon (explanation). Being a perceiver, an intelligent machine should literally create a phenomenal world, because the process of perception first defines relevant distinctions in the sensory environment.

The approach exposed here challenges the received picture of an archaeological explanation as an invariant structure. Solving archaeological problems is an activity. We have to change the way we understand explanatory concepts. They are not verbal labels we attach to some percepts by means of a previously existing rule but a cognitive action, or a requisite for the next action. Explanations should be based on purposeful, goal-directed mechanisms emerging from a dynamical system that has been calibrated by learning (trial and error, experimentation, analogy) to make the right choices in the proper circumstances.

What I am suggesting is that when explaining, our automated archaeologist conceptually navigates in a potential field of explanations looking for attractors (goals) and repulsions (constraints). Upon detecting the goal, the explanation moves toward it, executes it and then follows until another goal or constraint is found. It repeats this sequence of actions until it has returned all attractors in the potential field. Since the robot does not manipulate propositions, any account of automated explanation that would draw on connectionist principles would not be able to limit itself to principles of logical inference in describing how some belief was arrived at. On the contrary, it is necessary to rely on something like the notion of maximal satisfaction of soft constraints to describe how the machine behaves cognitively, and in *evaluating* its performance we would presumably consider whether the constraints it satisfied in arriving at its output state were the appropriate constraints. This would lead us to an evaluation of how an automated archaeologist has learnt, specifically, whether its training had resulted in ways that enabled it to respond to inputs in a manner that was most likely to meet its needs in the environment. This would constitute a major change, since epistemology has generally been pursued through conceptual analysis, not empirical inquiry.

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REFERENCES

Barceló J.A. 2008, *Computational Intelligence in Archaeology*, Henshey (NY), Information Reference Source, IGI Group Inc.

Bar-Cohen Y., Hanson D., Marom A. 2009, *The Coming Robot Revolution: Expectations and Fears about Emerging Intelligent*, *Humanlike Machines*, Berlin, Springer.

Borillo M. 1977, *Raisonner, calculer*, in M. Borillo (ed.), *Raisonnement et méthodes mathématiques en Archéologie,* Paris, CNRS, 1-31.

Brooks R. 1999, *Cambrian Intelligence: The Early History of the New AI*, Cambridge (MA), The MIT Press.

Carr C. (ed.) 1985, *For Concordance in Archaeological Analysis: Bridging Data Structure Quantitative Technique and Theory*, Boulder, Westview Press.

Clancey W.J. 1997, *Situated Cognition: On Human Knowledge and Computer Representations,* Cambridge, Cambridge University Press.

Clark A. 1993, *Associative Engines. Connectionism, Concepts and Representational Change*, Cambridge (MA), The Mit Press.

Clarke D.L. 1968, *Analytic Archaeology*, London, Methuen.

Clarke D.L. (ed.) 1972, *Models in Archaeology*, London, Duckworth.

Cowgill G.L. 1986, *Archaeological applications of mathematical and formal methods*, in D.J. Meltzer, D.D. Fowler, J.A. Sabloff (eds.), *American Archaeology, Past and Future: A Celebration of the Society for American Archaeology*, Washington, Smithsonian Institution Press.

Doran J.E. 1970, *Archaeological reasoning and machine reasoning*, in J.-C. Gardin (ed.), *Archaeologie et Calculateurs*, Paris, CNRS, 57-67.

Doran J.R. 1988, *Expert Systems and archaeology: what lies ahead?*, in C.L.N. Ruggles, S.P.Q. Rahtz (ed.), *Computer and Quantitative Methods in Archaeology 1987*, BAR International Series 393, 237-241.

Doran J.R., Hodson F. 1975, *Mathematics and Computers in Archaeology*, Edinburgh, Edinburgh University Press.

Francfort H.P. 1990, *Modélisation de raisonnements interprétatifs en archéologie à l'aide de Systèmes Experts: conséquences d'une critique des fondements des inférences*, in J.-C. Gardin, R. Ennals (eds.), *Interpretation in the Humanities: Perspectives from Artificial Intelligence*, London, The British Library.

Franklin S. 1995, *Artificial Minds*, Cambridge (MA), The MIT Press.

Gallay A. 1989, *Logicism: a French view of archaeological theory founded in computational perspective*, «Antiquity», 63, 27-39.

Gardin J.-C. 1980, *Archaeological Constructs*, Cambridge, Cambridge University Press.

Gardin J.-C. 1991, *Le calcul et la raison. Essais sur la formalisation du discours savant*, Paris, Editions de L'Ecole des Hautes Etudes en Sciences Sociales.

Gardin J.-C. 1993, *Les embarrass du naturel*, «Archives Européennes de Sociologie», 34, 152-165.

Gardin J.-C. 1994, *Informatique et progrès dans les sciences de l'homme*, «Revue Informatique et Statistique dans les Sciences Humaines», 30 (1-4), 11-35.

Gardin J.-C. 1998, *Cognitive issues and problems of publication in archaeology*, in W. Hensel, S. Tabaczynski, P. Urbanczyk (eds.), *Theory and Practice of Archaeological Research*, Warszawa, Institute of Archaeology and Ethnology, Polish Academy of Sciences.

Gardin J.-C. 2003, *Archaeological discourse, conceptual modelling and digitalisation: An interim report of the logicist program*, in M. Doerr, A. Sarris (eds.), *The Digital Heritage of Archaeology, CAA2002*, Heraklion, Crete, Archive of Monuments and Publications-Hellenic Ministry of Culture.

Gardin J.-C., Lagrange M.S., Martin J.M., Molino J., Natali-Smit J. 1981, *La logique du plausible. Essais d'épistemologie pratique en sciences humaines*, Paris, Editions de la Maison des Sciences de l'homme.

Gardin J.-C., Guillaume O., Herman P.O., Hesnard A., Lagrange M.S., Renaud M., Zadora-Rio, E. 1987, *Systèmes Experts et sciences humaines. Le cas de l'archéologie,* Paris, Eyrolles.

Gibbon G. 1984, *Anthorpological Archaeology*, New York, Columbia University Press.

Hassanien A.E., Abraham A., Vasilakos A.V., Pedrycz W. (eds.) 2009, *Foundations of Computational Intelligence*, 5 vols., Studies in Computational Intelligence, Berlin, Springer.

Hugget J., Baker K. 1986, *The computerized archaeologist: the development of Expert Systems*, «Science and Archaeology», 27, 3-12.

Iyida F., Pfeiffer R., Steels L., Kuniyoshi Y. (eds.) 2004, *Embodied Artificial Intelligence*, Berlin, Springer.

Jones T. 2007, *Artificial Intelligence: A Systems Approach*, Hingham (MA), Infinity Press.

Lagrange M.S. 1989, *Les systèmes experts et la recherche en archéologie et sciences humaines. Un point de vue pragmatique*, «Documentaliste», 26, 1, 11-15.

Langley P., Simon H.A., Bradshaw G.L., Zytkov J.M., 1987, *Scientific Discovery. Computational Explorations of the Creative Process*, Cambridge (MA), The MIT Press.

Luger G.F. 2008, *Artificial Intelligence: Structures and Strategies for Complex Problem Solving*, (6th ed.), Addison-Wesley.

Munakata T. 2008, *Fundamentals of the New Artificial Intelligence: Neural, Evolutionary, Fuzzy and More*, Berlin, Springer.

Pfeiffer R., Scheier C. 1999, *Understanding Intelligence*, Cambridge (MA), The MIT Press.

Puyol-Gruart J. 1999, *Computer Science, Artificial Intelligence and Archaeology*, in J.A. Barceló, I. Briz, A. Vila (eds.), *New Techniques for Old Times, CAA98, Proceedings of the 26th Conference (Barcelona 1998)*, BAR International Series 757, Oxford, Archaeopress, 19-27.

Read D.W. 1985, *The substance of archaeological analysis and the mold of statistical method: enlightenment out of discordance*, in C. Carr (ed.), *For Concordance in Archaeological Analysis: Bridging Data Structure Quantitative Technique and Theory*, Boulder, Westview Press, 45-86.

Read D.W. 1990, *The utility of mathematical constructs in building archaeological theory*, in A. Voorrips (ed.), *Mathematics and Information Science in Archaeology. A Flexible Framework*, Studies in Modern Archaeology 3, Bonn, Holos Verlag, 29-60.

Russell B. 1959, *My Philosophical Development*, London, Allen & Unwin.

Schiffer M.B. 1976, *Behavioral Archaeology,* Orlando (FL), Academic Press.

Shennan S.J., Stutt A. 1989, *The nature of archaeological arguments*, «Antiquity», 64 (245), 766-777.

Thagard P. 1988, *Computational Philosophy of Science*, Cambridge (MA), The MIT Press.

Wagman M. 2000, *Scientific Discovery Process in Humans and Computers*, Westport (CN), Praeger Publishers

Wilcock J. 1986, *A review of expert systems: their shortcomings and possible applications in archaeology*, in E. Webb (ed.), *Computer Applications in Archaeology 1985*, London, 139-144.

ABSTRACT

Twenty years after the consolidation of a true professional archaeology in search of a "scientific" dream, mathematics and computers made their appearance in the discipline. In the same way, the first essays dealing with "automatic archaeology" appeared in the 1950s, looking for standardization of archaeological description and statistical reasoning, but we had to wait for another 30 years until the appropriate technology was available. At the end of the 70s and beginning of the 80s, Expert Systems were considered as a true promise towards the independence of archaeological reasoning from subjectivity. Nevertheless, the rise of post-modernism and the radical critique, with its emphasis on subjectivity and situational context of the research effort generated considerable turmoil that, in appearance, buried the dream of an automatic archaeology. Research efforts in these domains of computational intelligence continued, however, especially in the domains of remote sensing and archaeometry. Modern technological developments like 3D scanning are responsible for a revival of interest in computational intelligence methods. Today, we are still far from the early dream of an automatic archaeology, but it is no longer a "nightmare". It is a technological reality that will contribute to a more professional and scientific-based archaeology.