AUTOMATIC PROBLEM-SOLVING IN ARCHAEOLOGY: A COMPUTATIONAL FRAMEWORK

One of the recurrent words in post processualist archaeology is the term *meaning*, maybe as a result of structuralism and semiotics influence. In this paper I deal with the computer *representation* of archaeological meanings from a processual view. I do not pretend to discover meanings computationally, but to study by means of a computer program the task archaeologists do. I am interested in "meanings" as a theoretical construct, and not as those "mental states" in past minds. Therefore, the computational analysis I propose is not a cognitive reconstruction, but a description of problem-solving mechanisms used by archaeologists. This analysis is not a defense of a positivist theory of archaeological meanings, nor a rebuttal of post-processualist or contextual ideas, but the strict analysis of the logical basis of archaeological discourse and reasoning.

1. Archaeological Meanings

Archaeologists usually say they need to discover the "meaning" of archaeological artifacts and ecofacts. They have also developed an enormous set of techniques to be able to obtain such "discoveries". In this context, "meaning" looks like a necessary category of real entities, therefore the task of scientists will be finding out that hidden characteristic.

In this paper, however, I propose a different definition for "meaning": "the uses of the artifact". "Meaning" is not an intrinsic property of any archaeological artifact. A single object can be used in many ways, depending on the context or the users' needs. Therefore, archaeological artifacts have not the same meaning in all circumstances, because there is not a single way of using it. It is not the object that chooses its utilization, but users according to contexts.

This definition of meaning is hardly novel in other disciplines, like Linguistics, Psychology or Computer Science (Searle 1979; Fodor 1981; Winograd 1983; Graesser, Clark 1985; Cummins 1989, among others). In literary and philological studies, the meaning of a message lies not only in the text, because the meaning of that text is a cognitive construct determined by different information sources. The first one is obviously the explicit content in the message (the text). The second source of information consists in the knowledge stored in the receiver's long-term memory. The third one constitutes the receiver's objectives. The fourth, and last source of information, is the context in which the message has been produced. It includes social relations between transmitter and receiver, shared knowledge between participants in communicative events, and principles of cooperative communication.

It is not very clear that an archaeologist is involved in a communication act when he tries to explain the archaeological record. Who is the transmitter in that situation? Artifacts themselves or the people who made those artifacts? Let us suppose that the artifact is the transmitter, because it is the only we know about the real transmitter. If that analogy were valid, then we would describe the "archaeological understanding act" as a system with the following components (Fig. 1):

— A transmitter (archaeological record): we suppose that the artifact's shape and deposition process are some kind of "text" containing "instructions" that allow us to understand the way in which that artifact was used.
— A receiver: an archaeologist with the technical training needed to understand the archaeological record.
— Knowledge accepted by the Scientific Community to which the archaeologist belongs, that is to say, a Scientific Theory.
— Goals proposed by the archaeologist before his beginning with the explanation.
— A context or situation, that is to say, a set of previously understood archaeological meanings, which affect the understanding of the new one. For example, the explanation of the "meaning" of a site depends on the meanings obtained from the analysis of other sites around it. In other words, the meaning of an artifact depends on the meanings of the artifacts around it.

From this discussion we must deduce that any interpretation of archaeological remains is a theory, even though it makes no reference to theoretical issues (Abelson, Lalljee 1988; Gardin 1990). Archaeological Meanings are cognitive constructs, the result of some inference mechanisms. Archaeologists cannot discover the meaning of the archaeological record; they have to "build" it, and to achieve this reasoning process archaeologists need "knowledge". This paper deals with the analysis of that knowledge.

2. Middle-Range Theories

One way to describe prior archaeological knowledge is by using the notion of Middle-Range Theories, proposed by Robert Merton in Sociology, and introduced in archaeology by Binford (1977; 1981) and by Raab and Goodyear (1984).

In "traditional Archaeology" the stipulation of meanings to data was implicit, and the main mechanism was common sense. According to Binford, most

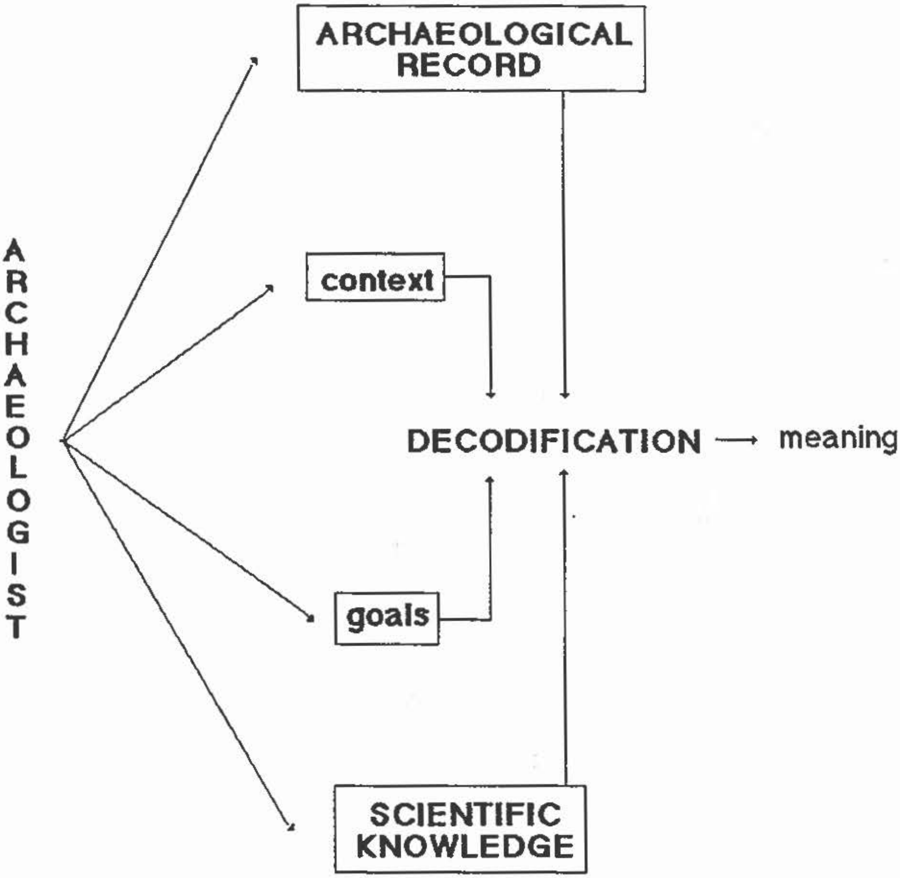

Fig. 1 — A scheme for building Archaeological Meanings.

justifications for such stipulations were ill-founded and generally wrong, produced by an alleged knowledge (a received knowledge) gained culturally, not through research in the strict sense of the word. The only way to solve the problem would be to use prior "scientific" knowledge. That is to say, a theory that relates the observed data to the processes that lead to them. However, this knowledge does not exist in the past. An archaeologist cannot certainly learn about the quality of the needed prior knowledge by studying the archaeological record, where meaning is infused by "common sense" justifications (BINFORD 1989). Prior knowledge has to be obtained independently of the analysis of the archaeological record.

Archaeologists usually obtain this kind of "scientific" prior knowledge through actualistic or ethnoarchaeological research. In this paper, the "production" of such knowledge does not interest us, but its use to solve a specific problem. In Binford's words:

> « We seek to analyze our data and partition our knowledge into general, uniformitarianistic knowledge that can serve as a frame of reference. Against this frame of reference we can project or compare other properties of the archaeological record that are also understood in generalizable but independent terms in order to isolate the organizational characteristics of past systems. In both cases, we would initially be seeking to recognize and understand properties that have general relevance to human actions ... These broad generalizable properties would then serve as an analytical frame of reference against which we could discern extensive behavioral variability. In the context of such similar organizations, very different 'behaviors' (in Schiffer's sense of the word) might be carried out » (BINFORD 1987).

Middle-Range Theories will then appear like universal generalizations, used as premises in a deductively reasoned interpretation of the archaeological remains. These universal arguments specify the archaeological observables that are expected to manifest particular phenomena of interest, and/or their expected nature of organization (CARR 1985, 1987).

In other words, we use Middle-Range Theories to deduce hypotheses. The logical pattern implicit in the use of such deductions is the following:

If **x** is an instance of **X**

And **X** is **Y**.

Then, **x** is **Y**.

"**X** is **Y**" is the result of some controlled experiment (a universal generalization obtained through observation of present dynamics) and we may use it as a criterion of relevance because of its testability. Interesting examples would be Hoffman (1985) and O'Shea (1984). The first one employs principles of lithic technology to select several variables for investigating morphological variation in a set of projectile points relevant to maintenance and reduction process. The second one specifies the kinds of mortuary variables that are likely to distinguish horizontally or vertically differentiated social segments; these variables allow the selection of the potentially relevant variables for a factor analysis.

Let us analyze the following example, from Binford (1984): the specific animal bones common at the residence of one family are generally low or absent at the locations of other consumer units within the same site. This condition derives from the fact that different anatomical segments are the units shared out by hunters. This means that the anatomical units, which are represented by only one element from a single individual, such as the skull or the neck, if present within one site will only be present at a single residence or consumer unit within the site.

The values of the three former variables are:

x = animal bones found at a particular residential unit

X = food

Y = sharing of food after collective hunting.
In "laboratory" conditions (for instance, in an ethnoarchaeological research) some archaeologists have observed that food is shared between all members of the hunting group. That action produces a non ambiguous material trace in the deposition of bones in each consumer (residential) unit. If we observe during the excavation of an archaeological site a deposition of bones similar to that obtained trough experimentation, then the conclusions will be the same.

The main limitation in Binford's description of Middle-Range Theories is the lack of structure within the Theory (see criticism in SCHIFFER 1988; WYLIE 1989). A Middle-Range Theory in Binford's terms looks like a set of independent universal propositions, used when an archaeologist finds an analogous case. Experimental results can be relevant, but the application of the theory to the evidence not. The process is most similar to an *assignation of meaning* than a *meaning construction*.

In this paper I mainly aim to formulate an adequate architecture for Middle-Range Theories, specifically one allowing computational implementation and execution.

3. AUTOMATIC PROBLEM-SOLVING

We can define a *problem* as a goal we want to achieve but we do not know how. Computer Scientists translate this single definition into the following terms: « the modification of an Initial State so that it matches an expression whose truth-value (or validation conditions) needs to be determined ». The solution to the problem will then be the truth-value or validation conditions of this expression (the goal). We validate a goal if there is a well-defined operator allowing the modification of the Problem Initial State until it matches the truth-conditions of the Final State or solution (see PEARL 1985; LAURIÈRE 1986; BROWN, CHANDRASEKARAN 1989; SHARPLES *et al.* 1989; BOY 1990; PARTRIDGE 1990).

In Archaeology, our goals are obviously the meanings of the archaeological record, that is to say, the social or technical uses of artifacts and ecofacts. We may formalize an *Archaeological Problem* in the following way: *how an artifact A (or set of artifacts A) is used by a community H in a context C*; where the context of utilization may be spatial, social, chronological, etc. (Fig. 2). This problem has four components:
— The artifact or set of artifacts (A).
— The human community who produced those artifacts (H).
— The context of use of the artifacts (C).
— The use of the artifacts (the *goal* of the problem).

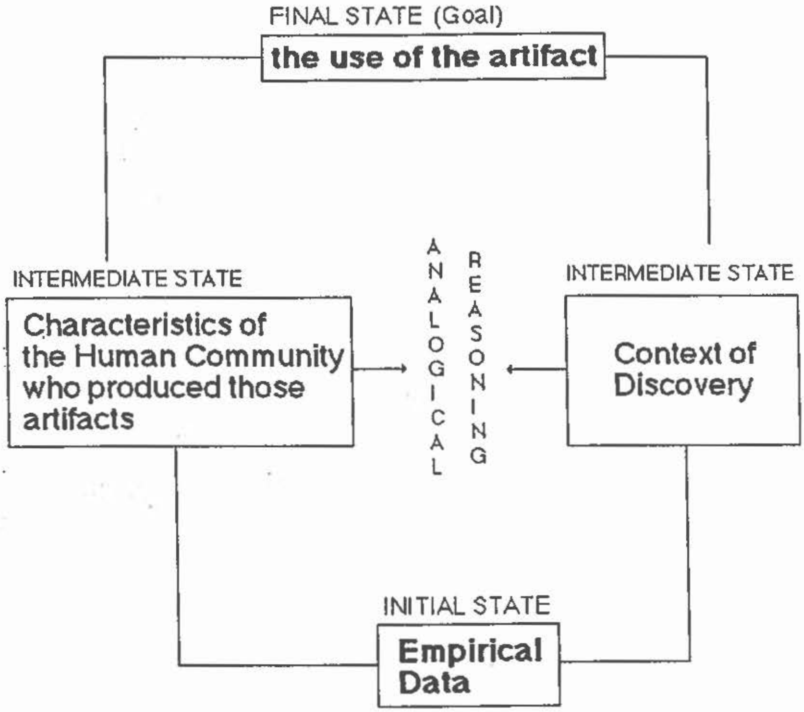

Fig. 2 — A decomposition on Archaeological Problems.

The task is then to *evaluate* the social uses of some specific set of artifacts (Final Situation or State) in terms of: a) their description, and b) all information available about the social, cultural or chronological context and about the human community who produced those artifacts (Initial Situation or State).

To solve any problem we need knowledge about all the different possible states. Final and Intermediate Situations (in other words, solutions and inference steps) have to be encoded in some explicit way. We call it the *problem* space, and we may represent it in procedural or declarative form. The first one follows a well-defined algorithm, which specifies explicitly how to find the output variables for any given input variables. If this were the case:

— There would be a definite criterion for testing any proposed solution, and a mechanizable process for applying the criterion. There has to be a description of the solution state, or a test to determine if that state has been reached.
— There would be at least one problem space in which the initial problem state, the goal state, and all other states that may be reached or considered can be represented, while attempting a solution of the problem. There

exists a set of terms for describing and characterizing the initial state, the goal state and the intermediate states.

— Attainable state changes (legal moves) in a problem space are the transitions from given states to the states directly attainable from them. There has to be a set of operators to change one state into another, with conditions for the applicability of these operators (SIMON 1973; POPLE 1982).

For instance, given the lengths of the two shortest sides of a rectangular triangle, "find the length of the third side" is a problem, which is solved *procedurally*. In other terms, there exists an operator "$\sqrt{(x + y)}$", which produces the required solution from the given initial state (the lengths of the two shortest sides); there also exists a criterion (Pythagoras Theorem) to validate that solution. In this case, solutions and inference steps are produced through an algorithm, and they use the Initial State as raw material.

However, "Meaning of x?", where (x) is an archaeological artifact, cannot be solved in the same way, because *"meaning" is not a fixed procedure*. In other terms, there does not exist any procedure to generate solutions and inference steps. In this case:

— There is not any single criterion to validate selected solutions.
— There is not any mechanizable procedure to apply that criterion.
— The Problem Space (the set of all possible solutions) is not well defined.

Are archaeological problems then unsolvable? Not at all. If we cannot "generate" problem spaces by means of a procedure, we may then represent problem-solving knowledge as a list of discrete and closed units. Those declarative units are successive states of the problem. We substitute equations for explicit sets of propositions. For example, there is no algorithm to discover the technical function of a lithic tool from its shape. We can implement a set of answers (knife, scrapers, spear...) and a set of decision rules for each one. The resulting program looks like a complex database and not like a mathematical procedure, and we may consider the problem-solving mechanism as a sequential *search* in a pre-existing problem space, using a finite number of particular decision rules.

4. HEURISTIC RULES AND MIDDLE-RANGE EXPRESSIONS

In a procedural problem-solving method we have probably enough with only one equation; but in a declarative problem-solver we need a great number of very specific decision rules. These rules look like Stimulus/Response pairs, where the Stimulus and the Response are sets of descriptive features defining a particular knowledge unit (or state of the problem). The representation format (*production rule*) is:

If A

Then B

Where A and B are two declarative states of the problem (for instance, an Initial and a Final State or two Intermediate States). This rule establishes a relationship among a set of facts in an IF clause and one or more facts in a THEN clause.

Using the previous example (BINFORD 1984):

If

the animal bones found at the residential unit (x) are different from the animal bones found at the residential unit (y)

and

in controlled laboratory situations it has been demonstrated that such differences in the animal bones deposition between consumer or residential units are the result of the sharing of food between the members of a hunting group,

then

people who lived and ate in (x) and (y) would belong to the same hunting group.

We have here three declarative knowledge units, two of them are states of the problem and the third one is a condition (or Middle-Range Expression) for the activation of that rule:

Initial State: the animal bones found at two residential units (Observation).

Final State: a single hunting group (an Anthropological Concept and a Theoretical Term).

Middle-Range Expression: differences in the animal bones' deposition between consumer and residential units are the result of food sharing between the members of a hunting group (Experiment).

"A single hunting group" is an explanatory concept, a declarative prior knowledge unit, and not the result of some mechanical procedure. The goal we want to achieve is to evaluate the expression: « people who lived and ate in (x) and (y) would belong to the same hunting group ». This evaluation is possible because we dispose of a middle-range expression (a condition) which activates a production rule expressing the association between the evidence and the interpretation.

The ideal form of any decision rule in a declarative problem-solver is:

IF

[EMPIRICAL DATA]

and

[ACTIVATION CONDITION] is a property of [SOLUTION]

and

there is an analogical link between [EMPIRICAL DATA] and ACTIVATION CONDITION]

THEN

[EMPIRICAL DATA] is an instance of [SOLUTION].

In other words, the linking between a particular evidence and a particular interpretation unit is only possible if the rule is made active. This situation succeeds only if there is some independent activation condition analogically linked to empirical data. Activation conditions are obviously the middle-range expressions.

Middle-Range Expressions are sufficient (and not necessary) properties of Interpretative Concepts and Theoretical Entities. Without them, Interpretations are passive sets of propositions, useless in a problem-solving task. They do not work as General Laws, but they reduce the range of possible interpretations for an archaeological problem: independent experimental results serve to make active Concepts, because they allow possible links between the Observation and the Theory. Nevertheless, given the fact that decision rules and declarative concepts are discrete units, their activation will be never definitive. We must deduce that there are other ways to make active an Interpretation. To solve this limitation, Computer Scientists and Cognitive Psychologists have introduced the notion of *heuristics* as an alternative to the "truth conditions" of procedurally obtained solutions (NEWELL, SIMON 1972, 1976; NEWELL 1973, 1980; SIMON 1973, 1979, 1983). The Heuristic Conditions for the Activation of a declarative solution are a set of some plausible criteria to accept or refuse the final state of a problem as its solution. That means that the solution is not "true", but "plausible": it is a good solution, although we cannot know if it is the best one we can produce with that set of declarative knowledge. Thus, Middle-Range Expressions are the Heuristic Conditions for the proper activation of Interpretative Concepts.

This is the most important aspect we have to learn from the above discussion: an Archaeological Middle-Range Theory is not a Universal Theory about Human Culture, but a kind of declarative problem-solving knowledge, *heuristically relevant* to a particular archaeological problem. Heuristic does not mean "subjective", but "a plausible way to use a particular declarative knowledge". Maybe there are infinite possible ways to use them, but we will use the only one we have tested.

5. AN INTELLIGENT DATABASE

Middle-Range Theories are usually very complex, because they cannot be reduced to single and independent expressions. In this chapter I will develop an example of "automatic" Middle-Range Theory, the GLADIUS project, actually underway at the Universitat Autonoma de Barcelona (Spain) (BARCELÓ 1991a, 1991b). The aim of the program is to analyze the complexities around the linking, structuring and spreading activation in a computer system containing a great number of middle-range expressions.

GLADIUS is an Intelligent Database, that is to say, a Database able to use its contents automatically to solve archaeological problems. To achieve this task, it does not contain simple data and search procedures, but complex knowledge units (concepts) and built-in inference mechanisms.

GLADIUS implements an archaeological theory about the social uses of artifacts. It answers questions like: « Did that human community use these objects as social symbols, that is to say, as symbols for social identity? » The components of this Theory are the following:

— Different sets of interpretative concepts extracted from standard social theory (Consumer Sociology and Economic Anthropology).
— Hierarchical relationships between the concepts.
— An activation mechanism that uses data sets containing empirical observations.
— An analogical mechanism that searches for new unexpected associations between concepts.

Concepts are represented using a computational data structure called « FRAME ». It is an individual object, defined by some attributes. For example (STUTT 1989):

PRINCIPLE:
name: marxist—principle—1
claim: cause (class division, conflict within groups)
grounds: common—sense—principle—2
PRINCIPLE:
name: common—sense—principle—2
claim: cause (divisions between groups based on X; conflict within groups based on X)
grounds: basic—ground

where "*name*", "*claim*" and "*grounds*" are attributes. GLADIUS uses three kinds of attributes:

— Structural: definition characteristics of each concept.
— Relational: the specific role of that knowledge unit in the problem-solving task, that is to say, some kind of meta-knowledge about the computer implementation of that concept.
— Activation Conditions: some "scientific" proposition generated by experimentation or by deduction about the strength of that concept and the nature of links converging on it from the other concepts in the system.

Concepts are organized in a hierarchical network according to the quantity of observational terms used to define their Structural Attributes: the more observational terms, the lower level in the network. For example, a Concept like "Sociotechnical Item" has a lower level than the Concept "Social Conflict". Inheritance links are defined between all hierarchical levels, in such a way that instances automatically receive information from their higher linked units.

Inheritance links only have an indirect relevance on the Activation Conditions attributes. There are some differences between the activation conditions for Low-Level Concepts and the activation conditions for High-Level ones. In both cases, these attributes contain middle-range expressions, but in the Lowest-Level Concepts they are expressed in observational terms, and in higher levels as a set of previously activated concepts.

For example, the concept "Sociotechnical Item" is the lowest concept in a chain whose terminal (highest) concept is "Social Conflict". Activation Conditions for the first concept are expressed in observational terms: « if object (x) has been found in a grave, then it is a Sociotechnical Item ». Activation Conditions for the concept "Social Conflict" are: « If the Concepts: (Sociotechnical Item), (Controlled Distribution), (Social Rivalry), (Appearance of Social Elites) are active, then the Solution will be (Social Conflict) ». Binford's Middle-Range-Expressions only appear in the Lowest-Level Concepts. The Activation Conditions for High-Level Concepts are also middle-range expressions, but they are more like Gardin's « Intermediate Propositions (Pi) » than Binford's « frames of reference ».

Lowest-Level Concepts are consequently the instances of High-Level ones, because they work as their activation conditions. Of course, the declarative links between them are also "scientific" and testable pieces of information, although not experimental (the number of observational terms is too reduced). Most of the time we implement them deductively, as a subdivision of the Highest ones. Not all the concepts in GLADIUS are organized hierarchically; only concepts with tested relationships are structured in "inference chains". The resulting system is a set of independent chains (which can be very long or very short), whose links will be established through analogical inference. By running the program we will obtain positive or negative tests of all these links, declarative or automatically generated.

GLADIUS also contains a set of unrelated knowledge units called Activation Units. They are not Interpretations or Concepts, but computational entities able to translate input information (empirical information contained in a classical Database) into the same terms as the Lowest-Level Concepts Activation Conditions.

First, the system assumes that the user has asked for a specific problem. The user introduces some empirical descriptive features, which are read by the system and stored in the Activation Unit. This unit activates the lowest instances of Theoretical Entities, and begins the spreading activation through the concept hierarchy. The procedure may be divided into the following operations:

— ACTIVATION - The user introduces some empirical data representing a real phenomenon (Description). The user may introduce them in ASCII Files.

— CREATING AN INITIAL STATE - Using heuristics derived from the problem (the goals expressed by the archaeologist), the system automatically creates a representation of the problem initial state, and stores it in the Activation Units. These computational entities look like Carr's Entry Models which link data to the inference mechanism (the technique) and not to the High-Level Interpretation. In other words, a general model or description of the "form of organization" of the archaeological observables that represent the phenomenon of interest (the goal we want to evaluate) (CARR 1985, 1987). Therefore, Activation Units would inventory all general forms of organization of artifacts and artifacts' types that might logically occur in various environmental and behavioural contexts along various behavioural and formation-relevant dimensions of variability. Each Unit is associated with a particular model of social formation process that could have generated the form of organization described in the input data file. The quantity of such activation units can be very great, unrelated to the quantity of Higher-Level Concepts in the systems. Instead of the mathematical nature in Carr's entry models, GLADIUS's Activation Units are logical systems (production rules) (see FORSYTH 1989, FORSYTH, RADA 1986 about the use of rules' systems for pattern recognition purposes).

— CALLING KNOWLEDGE UNITS - Activation Units represent the problem Initial State, and their function is to call the lowest theoretical entities. These concepts have their own activation conditions or experimental results about the association between some specific initial state and a concept expressed in observational terms. The Instantiation procedure looks like a Multi-Expert System, and their rules have the following representation format:

If

(x) is an attribute in some Activation Unit

and

(y) is a middle-range expression stored in a Concept

and

(x) is analogically linked to (y)

then

Activate that Concept.

The analogical relationship between (x) and (y) is the result of an independent inference mechanism (see GICK, HOLYOAK 1980, HOLYOAK, THAGARD 1989, KEANE, BRAYSHAW 1988). This mechanism uses empirical data as input and searches in the problem space if there is a low-level concept with a property "similar" to those in empirical data. Once the link between empirical data and low-level concepts is established, the Initial State of the problem inherits other properties from that concept. The inference mechanism is represented in Fig. 3.

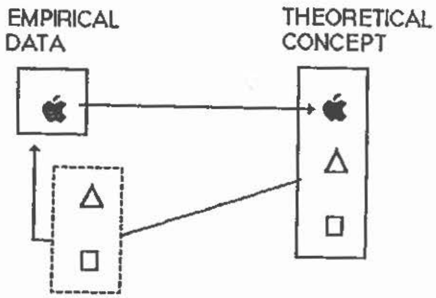

Fig. 3 — A mechanism for analogical inference.

Low-Level Concepts do not contain information about their relationship with the evidence, but with the Activation Units. This information is exclusively expressed by the rules. In this way, the modification, updating and controlled experimentation with particular parts of the system become easier.

— USING THE CONCEPT HIERARCHY - There are two kinds of links between concepts: hierarchy relationships (declarative and explicit links) between the objects within a class and analogies ("intelligent" links) between classes. The system automatically generates the analogical links at run-time, while the hierarchy relationships are implemented by the user after testing. The difference between them lies in the validated character of declarative links. Both are used as paths to guide spreading activation. In the first case, a High-Level Concept is made active because its Lower-Level Concepts are also activated. Given the fact that the Activation Conditions in each concept are independent from the Activation Conditions in other concepts, if some concept is not activated by the actual state in Activation Units, the inference chain is interrupted, and the Highest Concept will be the last activated one (Fig. 4).

— CONSTRUCTING A FINAL SOLUTION - The answer is not the last activated theoretical entity, but a computational object (called Interpretation) which contains all the inferences, activations and modifications in the working memory.

— REACTIVATION - To test unexpected associations or to replicate previous results, the system can descend the hierarchy chains that it has used and explore alternative forks. For example, let us suppose we are studying a group of prehistoric artistic representations (decorated stelae): if the Iconographic Heterogeneity in a geographical and chronological series of stelae has allowed the System to confirm the existence of an important Social Differentiation in this community, then in the Reactivation mode the system chooses an alternative hypothesis to the association "Iconographic Heterogeneity →Social

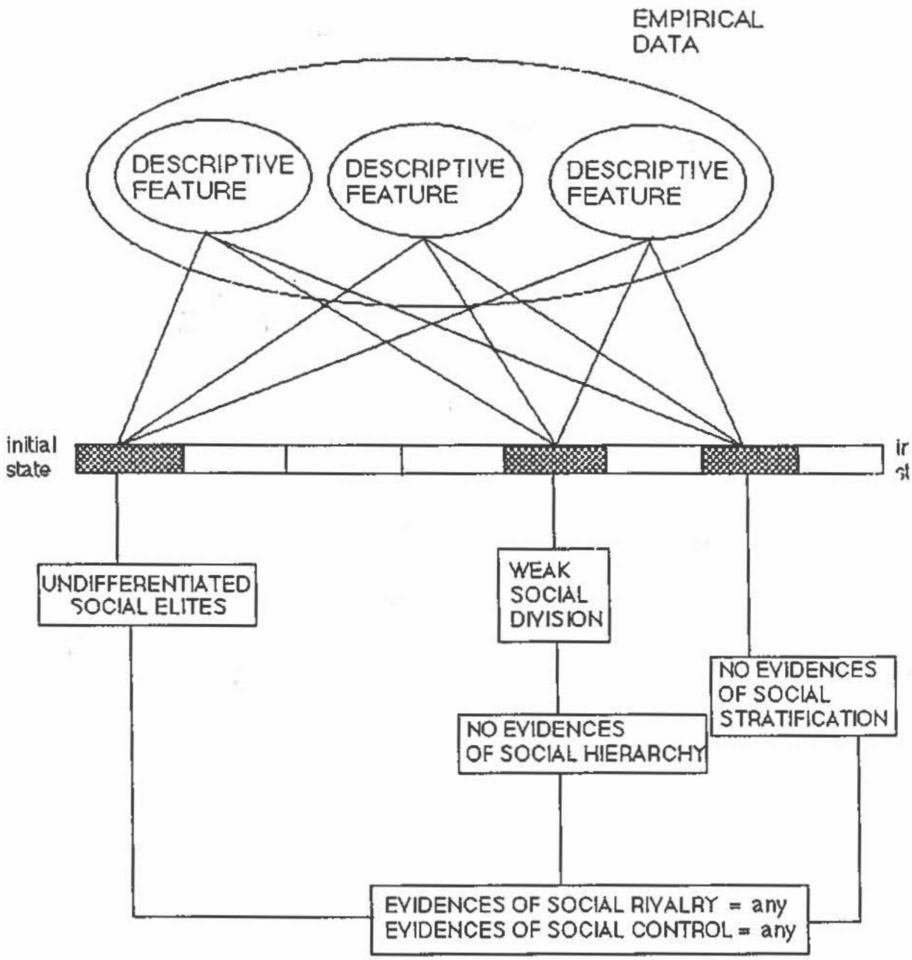

Fig. 4 — Conceptual hierarchy in the GLADIUS system.

Differentiation", perhaps "Functional Diversity in Settlement Structures → Social Differentiation". In other words, in order for the system to confirm the existence of Social Differentiation in this community, it must discover if there is Iconographic Heterogeneity between Stelae and Functional Diversity in Settlement Structures. The same problem has always different initial states.

To sum up, GLADIUS is a little more complex than classical Expert Systems: in a rule-based system, for example, a rule is selected for firing when the elements in the working memory match the elements of the rule's condition; a match requires either that the elements be identical or that the condition element be a variable of which the working-memory element is an Instantiation. In contrast, the analogical mapping engine and the declarative hierarchy chains allow the generation of mappings between different kinds of elements. In GLADIUS, the concept-firing process is essentially forward-chaining from starting conditions (empirical information stored in a database file) to goals (interpretations). In contrast, the validation procedure is essentially back-chaining, trying to evaluate the results using different and alternative inference steps.

The activation of concepts spreads in a controlled manner (as specified in the problem-solving goals). Concepts declaratively linked to previously fired concepts become active, making available the inference chains employing those concepts. At this level, middle-range expressions are totally relational. For example:

SOCIAL CONFLICT:
    Attributes: (...)
    Activation Conditions: (Appearance of Social Elites) is ACTIVE
APPEARANCE OF SOCIAL ELITES:
    Attributes: (...)
    Activation Conditions: (Social Rivalry) is ACTIVE
                                        (Social Differentiation) is ACTIVE

Let us suppose that (Social Rivalry) and (Social Differentiation) are unrelated concepts belonging to different inference chains. Empirical data only allow us to fire the (Social Differentiation) Concept. The inference chain stops at this point, starting then the analogical engine: the most similar concept to the actual state of the working memory (or the Interpretation Object) is probably the (Appearance of Social Elites) Concept. It is an analogical result, and not a solution to our problem. To obtain a good solution we have to validate the linking between the actual contents in the working memory and the analogically activated Highest Concept.

The best and easier way to generate that validation is by exploring alternative inference chains. In our example, given the fact, we have used the (Social Differentiation) Chain to activate a plausible solution, the system will explore the (Social Rivalry) Chain. If all the Activation Conditions associated with this concept may be active by the input database, we will conclude that the analogical linking is a valid one. If this linking is validated in different cases it will be changed into a declarative hierarchical link.

The GLADIUS Project shows that the relation between archaeological artifacts and middle-range expressions (or Activation Conditions) is not of similarity (correspondence among properties), but of analogy (correspondence among relations and rules). This analogy is not a necessary property of concept, but a scientific construct, the result of some reasoning testable process. Analogy is a multilevel reasoning process, a kind of activation function allowing the search of the best heuristic solution in an enormous problem space. The mapping between interpretative concepts (the base) and empirical data (the target) is not direct, but needs multiple inference steps, which are analogies too. We must consequently characterize Archaeological Interpretations as complex inference chains, in which different kinds of middle-range expressions are needed.

GLADIUS is not yet an "intelligent" program, but a project to build a future Archaeological Theory. Its limitations reproduce the limitations of a scientist at the beginning of his task: he knows a great number of middle-range expressions, a great quantity of empirical data, and a few High-Level Concepts extracted from other Theories. The goal is to experiment if a Theory can be built only using those components.

Only by running this system or another one like it, will we discover if an "Automatic" Theory (a theory expressed by means of a computer program) is or is not possible.

6. Conclusions

Archaeological Theories, like all theories, are symbolic structures, where symbols and relationships between symbols can be expressed by means of:
— linguistic sentences
— mathematical equations
— logical propositions.
Some interesting work has been done on mathematical representation of archaeological theories (Read 1987, 1990), but such approaches have not been very successful, maybe because Social Sciences cannot be exclusively represented by mathematical models, or because archaeologists are incapable of communicating between themselves using mathematical expressions. As a consequence, archaeologists tend to express their theories by means of linguistic sentences, which is inadequate, given the fact that Natural Language obstructs objectivity (Gardin 1990). A representation in terms of logical propositions appears then as the best representation tool available to build social theories.

Artificial Intelligence scientists are now exploring this possibility (see Langley *et al.* 1987; Shrager, Langley 1990; Gardin *et al.* 1989; Tiles *et al.* 1990). The GLADIUS project is another attempt in this direction. It proposes an analogy between the structure of Archaeological (and Social Sciences) Theories and the mechanism of Turing Machines: given some empirical data (observation of the archaeological record) and a Knowledge-Base (constituted by High-Level Concepts and their middle-range correlates), we have to explain the particular case (the archaeological record) by means of the Knowledge-Base (the Theory). The logical mechanism is modus ponens.

The "creation" of High-Range Theories is an unsolved problem in GLADIUS. Most of the scientists use Interpretative Concepts existing in his/her social ideology, that is to say, produced by an alleged knowledge (a received knowledge) gained culturally, not through research in the strict sense of the word. Therefore, theoretical entities are, in a certain sense, "independent" from the scientist's goals. Some interesting work has been done on this subject (STOKOCZWSKI 1991), but we need more empirical research on the cognitive basis of scientific explanations.

The real interest of GLADIUS and Intelligent databases for archaeologists is not the production of new data or new explanations, but reasoning about the way to connect both pieces of information. Concepts are expressed always in theoretical terms, and empirical data in observational ones. Their logical nature is so different that it is not possible to establish a connection between them. This is the function of Middle-Range propositions, which express the result of some controlled experiments. We have also seen that Middle-Range propositions are not isolated affirmations, but a hierarchically organized theory in its own way.

The last important idea in GLADIUS is "Activation": a logical function that measures the association level between evidence and interpretation. As we have seen it depends on the particular values of the different middle-range expressions we have obtained experimentally and implemented in the program. Consequently, any activation function is partial, and does not explore all possible alternatives, but only the declared ones. Middle-Range Theories will not then be independent knowledge bases, but heuristic rules whose function is to guide the search for the best solution in a potentially very great set of interpretations (the greater the problem space, the more useful the resulting automatic theory).

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ABSTRACT

In this paper I have tried to build a *Computational Theory*. In other words, a "theory" implemented in a computer program. When using a computational theory we try to solve scientific problems, that is to say, we do not retrieve data units, but we "instantiate" a solution for the problem. I have formalized the concept of *Archaeological Problem* in the following way: *how is used an artifact (or set of artifacts) by a community in a specific context.* The task is then to *evaluate* the social uses of some specific set of artifacts (Final Situation or State) in terms of: a) their description, and b) all information available about the social, cultural or chronological context and about the human community who produced those artifacts (Initial Situation or State).

We may then represent problem-solving knowledge as a list of discrete and closed units. Those declarative units are successive states of the problem. We substitute equations for explicit sets of propositions. We can implement a set of answers and a set of decision rules for each one. The resulting program looks like a complex database and not like a mathematical procedure, and we may consider the problem-solving mechanism as a sequential *search* in a preexisting problem space, using a finite number of particular decision rules.

Some interesting work has been done in mathematical representation of archaeological theories, but such approaches have not been very successful, maybe because Social Sciences cannot be *exclusively* represented by mathematical models, or because archaeologists are incapable to communicate between themselves using mathematical expressions. As a consequence, archaeologists tend to express their theories by means of linguistic sentences, which is inadequate, given the fact that Natural Language obstructs objectivity. A representation in terms of logical propositions appears then as the best representation tool available to build social theories.

Artificial Intelligence scientists are now exploring this possibility. In this paper I propose an analogy between the structure of Archeological (and Social Sciences) Theories and the mechanism of Turing Machines: given some empirical data (observation of the archaeological record) and a Knowledge-Base (constituted by high-level concepts and their middle-range correlates), we have to explain the particular case (the archaeological record) by means of the Knowledge-Base (the Theory). The logical mechanism is modus ponens.