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MOSAIC: A Macro-Connectionist Expert Systems Generator

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Abstract—*Artificial Intelligence (AI) and Artificial Neural Networks (ANNs) are two scientific disciplines which have concentrated tremendous efforts in the understanding and reproduction of human cognitive functions through simulation. Integration of concepts from both disciplines becomes increasingly necessary and natural. Expert systems involve several different aspects of cognition and, therefore, are interesting as a domain of integration. Concepts of each discipline must be selected in order to produce a synergism when they are merged together. At present, three approaches might be proposed: the interfacing approach, the extension approach, and the integration approach. In this article, we describe MOSAIC, the acronym for "Macro-connectionist Organization System for Artificial Intelligence Computation," which corresponds to the integration approach and which presents a number of basic features: The* numerical connectivity aspect, *the* autonomy of functional structured entities, *and the* recursive construction of assemblies of entities. *These features allow MOSAIC to manage several inference strategies (forward chaining, backward chaining, and implicit deduction), to acquire knowledge explicitly or by a fast unsupervized learning from examples (Estimated Connection Weights Learning), to process uncertain and partial information, to integrate both declarative and procedural knowledge and to be an open system. Finally, medical expert system applications are described.*

INTRODUCTION

ONE OF THE most exciting challenges for the scientific community is to combine cognitive psychology and neurobiology concepts. Computer science is central in reaching this integration because it allows the construction of models for both domains. Artificial Intelligence (AI) provides tools for the computational study of cognitive psychology models. Similarly, Artificial Neural Networks (ANNs) provide valuable solutions for simulations of cognitive capacities, essentially at the perception level.

This integration is not straightforward because a number of underlying differences exist between AI models, termed "Classical models," and "Connectionist models." The nature of inference, in connectionist systems, is only *numerical,* whereas that in Classical models is *logico/syntactic, and semantic.* Relations, in Connectionism, are mainly *causal* and represent associations. In Classical models, relations are structured (for example, conceptual dependencies (Schank & Colby, 1973)) and allow combinations. Characteristic behavior, in Connectionism, is *self-organization.* In Classical models, the *combinatorial capability of structures* in mental representations is one of the major features. These characteristics highlight the most important distinctions of the two approaches, but also how they can be complementary. AI is already multidisciplinary; it incorporates elements of psychology, linguistics, mathematics, and even philosophy, but usually rejects biologic concepts. Of course, there are some exceptions such as the genetic algorithm for learning (Booker, Goldberg, & Holland, 1989; Holland, 1973).

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In the light of recent progress in the neurobiology of cognition (Changeux & Konishi, 1987; Eimas & Galaburda, 1989), and with ANNs, (Pfeifer, Schreter, Fogelman-Soulie, & Steels, 1989), it would be interesting to extend this multidisciplinary notion by integrating the biologic concepts in AI.

The attempts to merge AI and ANNs have been based on three principal approaches: the first corresponds to the implementation of existing AI concepts (for example, rule-based systems) into connectionist architectures to attempt to improve their capabilities. The second concerns the development of interfaces between Classical models and Connectionist systems (for example, Hendler, 1989). MOSAIC, the acronym for *Macro-connectionist Organization System for Artificial Intelligence Computation,* is a third approach: the development of a new architecture situated at a different neural organization level (assemblies of neurons) capable of taking both a number of Classical models and ANNs concepts into consideration. In Connectionist systems, the processing units correspond to single neurons. However, there are an increasing number of neurobiologic studies of the role played by assemblies of neurons in mental representations (for example, Delacour, 1987; Dudai, 1987).

This article discusses the fundamental notions of the functional organization level in an ANN, and explains why MOSAIC is situated at a *macro*-Connectionist level. It also shows why this level allows an efficient symbol-processing approach. A number of basic features characterize MOSAIC: the *numerical connectivity aspect,* the *autonomy of functional structured entities,* and the *recursive construction of assemblies of entities.* These features allow MOSAIC to manage several inference strategies (forward chaining, backward chaining, and implicit deduction) to acquire knowledge explicitly or by learning from examples, to process uncertain and partial information, to integrate both declarative and procedural knowledge, and to be an open system. Finally, medical expert system applications are described.

1. FUNCTIONAL ORGANIZATION LEVELS

Connectionist systems correspond to the implementation of a certain functional organization level of ANNs. In neurobiology, the notion of functional organization is fundamental: "The specification of such levels should precede any theorical approach, and might even constitute the substance of a full theory." Different functional organization levels can be distinguished: "The first level, the architecture of which can be related to functional characteristics of the nervous system, is the *"cellular level"* . . . Another level of organization, referred to as the *"circuit level"*. . . The mutual relations of individual neural circuits define another level of organization. . . . The cognitive level lies within reach of this *"meta-circuit level."* At each level, different properties emerge according to the nature of the basic entity and the mode of communication. At the cellular level, the functional properties depend on the axonal and dendritic branches and the synaptic contacts. At the circuit level, the basic functional entity is the neuron. It is the connectivity between these single neurons which exhibits the functional capabilities of the circuit. Most connectionist systems are, at this functional organization level, consistent with the observations of Changeux and Dehaene (1989). Indeed, a connectionist system is an artificial neural circuit providing a single precise type of function, for example, letter recognition (Fukushima, 1988), speech recognition (Elman, 1987), reading aloud (Sejnowski, 1987). At the meta-circuit level, the functional properties result from mutual communications between individual neural circuits. This organizational level presents a very interesting feature because it allows interactions between different functional entities via the same kind of communication system, that is, nervous propagation. In the implementation of cognitive functions, one of most difficult problems is to integrate different kinds of functional properties, in particular, different kinds of knowledge representation and processing in the same system. The purpose of MOSAIC is to define and implement computational features of the meta-circuit level for symbol processing, which is why MOSAIC corresponds to a *macro*-connectionist approach. It is interesting to use neurobiologic structures; on the one hand, they correspond to general information processing systems, and on the other, during their implementation some new functionalities can emerge. However, when certain cognitive functions cannot be implemented with a known neurobiologic structure, a "functional block" corresponding to a black box is constructed.

2. BASIC CONCEPTS OF *MOSAIC* APPROACH

To date, the molecular and the cellular levels have constituted major axes of research in neurobiology. The study of these organizational levels has elucidated a number of learning mechanisms (for example, habituation, sensitization (Carew, 1987; Kandel et al., 1983). The understanding of activation and propagation mechanisms (excitation threshold, axonal and dendritic propagation, synaptic contacts, etc.) is becoming clear in terms of molecular and cellular processes. More recently, another organizational level, that is, assemblies of neurons, is being studied. This approach does not only rely on the organization of one assembly of neurons, which constitutes a structured entity, but also on the organization of and information-propagation mechanism between assemblies of neurons. There is a notion of recursivity at this level. Indeed, different assemblies of neurons can be viewed both as separate entities and as a single composite assembly. This functional organization level, is sometimes termed *macro-connectionism* (Delacour, 1987) in neurobiology.

The objective of MOSAIC is not to reproduce exactly every behavior or structure of this neural organizational level. The analysis of this level from a computing point of view highlights a number of basic concepts which constitute the guidelines for the development of the MOSAIC approach. The aim of this approach is to integrate, in a single architecture, a number of features of ANNs and of AI, and to provoke the emergence of new functionalities. Three principal features characterize the MOSAIC approach:

- the *numerical connectivity aspect* allowing the learning from examples and numerical inference propagation;
- the *autonomous functional structured entities* allowing the management of structured complex information, the modularity, and to have an open system; and
- the *recursive construction of assemblies of entities* allowing the organization of a knowledge base and the interactions between knowledge bases.

2.1. A General Communication System

The connectionist approach implements expert systems managing only one type of knowledge representation structure (for example, production rules). A second generation of expert systems represent a significant research thrust. These expert systems are characterized by the integration of different kinds of knowledge representation structures (for example, production rules and objects). The problem encountered in the development of these systems is the management of interactions between the different knowledge representation structures and, therefore, between the different inference processes. A *meta-inference process* is necessary to realize a global control on different inference processes. In MOSAIC, these problems can be taken into account because its communication system is unspecific and, therefore, polyvalent with regard to entities manipulated. The objective is to construct a general inference process based on a numerical propagation mechanism, to allow the management of more specific processes. This would allow the creation of a general communication system (Figure 1). To reach this objective, the notion of communication envelopes is introduced and will be described in detail. To summarize, MOSAIC is a general communication system for structured entities capable of recursive construction.

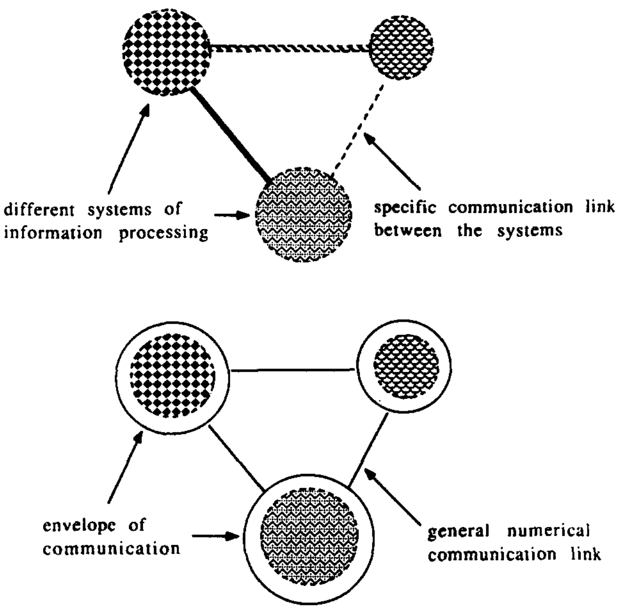


FIGURE 1. A general Communication System.

2.2. Dynamic Network Organization

Unlike most connectionist systems, MOSAIC is not a fully connected network. In addition, its general organization is not based on the three *static* layers of connectionist architecture: input, hidden, and output layers. In MOSAIC, the different layers are dynamically defined. Local or distributed representation depend on the level being considered. A node of the network can be considered as a layer and a layer as a node. This characteristic is due to the recursive definition of functional nodes in MOSAIC's network. With any one network connectivity, different hierarchical organizations are possible depending on the information input. We are going to describe in detail the node structure, termed *Neuronic* in MOSAIC. A knowledge base corresponds to a Neuronics network.

3. NEURONICS

A Neuronic is composed of three principal components: the *Nominal Zone*, the *Communication and Activation Envelope*, and the *Internal Process* (Figure 2). Only the Nominal Zone is mandatory for the definition of the Neuronic.

3.1. The Nominal Zone (NZ)

In the Nominal Zone, four types of information can be stored: the name of the Neuronic, any synonyms, the reliability coefficient, and the order of propagation. Only the name of the Neuronic is mandatory in the Nominal Zone.

```
Nominal_Zone_Description :: =
  $NZ: "NAME OF NEURONIC" [R] [^→];
  [{"EVENTUAL SYNONYMS";} . . .]
```

R represents the reliability coefficient of the Neuronic validation, and can vary from 0 to 100. If **R** is equal

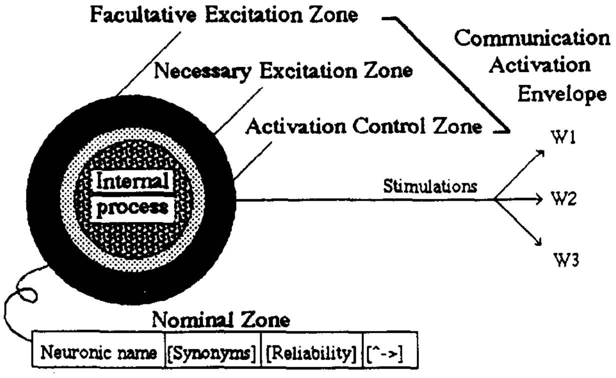


FIGURE 2. Structure of a Neuronic.

to 0, the information has no reliability. If **R** is equal to 100, the information is absolutely reliable. By default, the value of **R** is equal to 100. The coefficient **R** can only be defined when the Neuronic has insufficient stimulation in its Excitation Zones (these zones will be described).

In MOSAIC, the calculation of the connection weights differ depending on whether the knowledge was acquired explicitly or by learning from examples. In the first case, the effective value of the connection weight is modulated as follows by the reliability coefficient **R**:

```
$NZ:  "A" R;
$NZ:  "B";
$FEZ:  "A" → W(A, B);
```

$$W(A,B) = \frac{R*W(A,B)}{100} \tag{1}$$

The calculation of the connection weights, for the learning from examples will be described below.

The element ^→ indicates that the propagation of the validation of a Neuronic must start before the execution of the Internal Process. By default, the Internal Process is executed after the propagation has been started. This allows better management of parallel information processing.

3.2. The Communication and Activation Envelope (CAE)

The Communication and Activation Envelope has two principal roles in MOSAIC: the first allows *communication* between Neuronics. The envelope constitutes a standard interface between Neuronics which enables communication between functional entities processing different kinds of information. This communication role is secured by two excitation zones: the *Necessary Excitation Zone* (NEZ) and the *Facultative Excitation Zone* (FEZ). The second role concerns the activation control of the Neuronic. This role is carried out by the *Activation Control Zone* (ACZ). This checks information inputs arriving on the excitation zones. The activation of a Neuronic induces the execution of its Internal Process and propagation.

Knowledge can be acquired both explicitly and/or by learning from examples. Explicit knowledge acquisition corresponds to the descriptions of Neuronics, in particular, of the excitation zones. To define the excitation zones below, we need a number of syntax definitions (expression of Neuronics, Neuronics):

```
Neuronic_expression ::=
  Neuronic |
  ! Neuronic |
  Neuronic_expression and Neuronic |
  Neuronic_expression and ! Neuronic |

Neuronic ::= "string"
```

where the element "!" means "not."

3.3. The Necessary Excitation Zone (NEZ)

The Necessary Excitation Zone indicates the elements which are absolutely necessary for the validation of a Neuronic. They are not always sufficient. For example, wheels are absolutely necessary for a car, but are not sufficient to define a car.

```
NEZ_Description ::=
  $NEZ: {nez_expression;} . . .

nez_expression ::=
  Neuronic_expression |
  Neuronic_expression → +
```

Example:

```
$NEZ: "YOUNG MAN" and ! "DIABETES";
```

The validation of only one nez_expression is sufficient to validate the Necessary Excitation Zone. The different expressions are implicitly linked by the logical operator **or**. When the element "→ +" is indicated for a given nez_expression, this element represents a necessary and sufficient condition for the validation of the Neuronic "A."

3.4. The Facultative Excitation Zone (FEZ)

For a given Neuronic "A," the evocation or rejection elements must be connected on its Facultative Excitation Zone. There are two formalisms in the definition of the Facultative Excitation Zone: One for the human expert (explicit knowledge acquisition), and one another for the system when it acquires knowledge by learning from examples. The formalism for an explicit description of the Facultative Excitation Zone is as follows:

FEZ_Description ::=
  $FEZ: { fez_expression; } . . .

fez_expression ::=
  Neuronic_expression → Impact |
  fragmented_expression → Impact

fragmented_expression ::=
  Neuronic → Impact |
  Neuronic → Impact fragmented_expression → Impact
  → Impact

Impact ::= W | + | −

W ::= a number included in [−100, 100]

When a fez_expression (Facultative Excitation Zone expression) is validated, it involves a certain type of impact on the target Neuronic. These different types are:

- *Explicit connection weight* (→ W). The explicit connection weight is a measure of the reliability and the specificity of information. When the human expert explicitly determines the value of a connection weight, he implicitly takes both the reliability and the specificity of information into consideration. In rule-based systems, the certainty measure confuses these two aspects of information. It is not always possible to define these features when there is no available statistical data (e.g., the rate of reliability of a test, and its specificity for a given pathology). However, when possible, it is valuable to take the separation of these two parameters into account, because, during reasoning, some modifications according to the context may be necessary. In MOSAIC, these two aspects of information can be taken into consideration separately. The connection weight $W(i, A)$ expresses the evocation or the rejection strength of a fez_expression i on the Neuronic target "A." However, if among Neuronics constituting the fez_expression i the reliable coefficients are defined, the final value of the connection weight is calculated as follows:

$$W(i, A) = min\{Rj\} * W(i, A) \tag{2}$$

where j is the j^{th} Neuronic constituting the fez_expression i.

- *Sufficient validation stimulation* (→ +). Here, if the fez_expression i is validated, it will automatically involve the validation of the target Neuronic "A." This validation is immediate, the system does not take the other stimulations, even negative, into consideration. If this is the case, the fez_expression i is sufficient to validate the Neuronic "A."
- *Sufficient inhibition stimulation* (→ −). This corresponds to the opposite of the previous case. If the fez_expression i is validated, it will automatically result in the inhibition of the target Neuronic "A." This inhibition is immediate and the fez_expression i is sufficient to inhibit the Neuronic "A."

Example:

$FEZ: "A" and "B" → +;
  "C" → 80;
  "E" and ! "F" → −80;

3.4.1. *Fragmented Stimulations.* The definition of the fez_expressions allows *fragmented stimulations:*

$$\$FEZ\text{: ``}k\text{''} \rightarrow W(k, A) \textit{ and} \cdots \textit{and ``}m\text{''} \rightarrow W(m, A) \rightarrow W(k, m, A);$$

$$W = \begin{cases} W(k, A) & \text{if ``}k\text{'' is validated} \\ \cdots & \\ W(m, A) & \text{if ``}m\text{'' is validated} \\ W(k, m, A) & \text{if ``}k\text{'' and ``}m\text{'' are validated.} \end{cases} \tag{3}$$

This allows the human expert to express the relative dependence of signs:

$$W(k, m, A) < W(k, A) + W(m, A) \tag{4}$$

or their synergic associations:

$$W(k, m, A) > W(k, A) + W(m, A). \tag{5}$$

3.4.2. *Excitation State.* The Excitation state of a Neuronic "A," $ES(A)$, is only updated by stimulations that this Neuronic receives on its Facultative Excitation Zone:

$$ES(A) = \sum_{i=1}^{n} W(i, A)E_i \tag{6}$$

where n is the number of fez_expressions connected to the Facultative Excitation Zone of the target Neuronic "A," where $W(i, A)$ expresses the connection weight of the fez_expression i and where E_i is the activation state of the Facultative Excitation Zone expression i.

3.4.3. *Connectivity of Neuronics Expressions.* The expressions described above are interpreted by a parser which examines the excitation states of Neuronics to conclude if they are validated, inhibited, or undetermined. This corresponds to a logic with three states. It should be possible to construct a Neuronic network corresponding to the connectivity described by the expressions where the connectivity is described by the expressions. The structure of Neuronics allows this generation. This is interesting because the Neuronic networks allow a more efficient inference propagation than the interpreter.

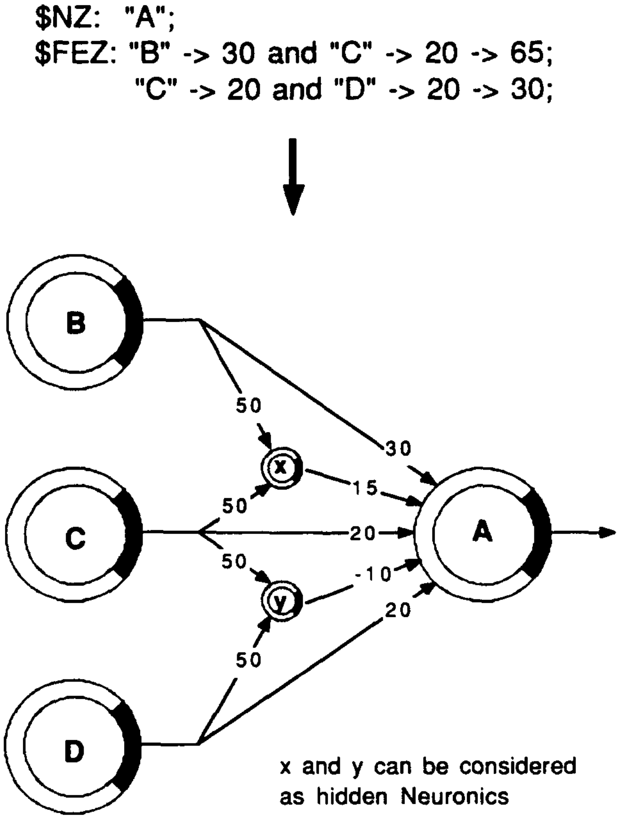
Example:

$NZ: "A";
$FEZ: "B" → 30 and "C" → 20 → 65;
"C" → 20 and "D" → 20 → 30;

In this case, for each expression the interpreter must verify, for each Neuronic, whether it has already participated in a stimulation. In the example, if the interpreter does not verify the occurrences of "C," the Neuronic "C" will stimulate the Neuronic "A" twice. With a network, this control is automatic (Figure 3). Another interesting feature of the network is the possibility of modulating the hidden Neuronics constituting this network. These Neuronics can also generate questions according to their excitation state.

3.5. The Activation Control Zone (ACZ)

The Activation Control Zone allows the system to check whether the input information has or has not produced enough stimulations to validate the Neuronic. There are three conditions which allow the validation of the Neuronic: first, there is validation if there is a fez_expression having "→ +" at its end, and which has been validated. This expresses a sufficient condition. Second, there is validation if there is "→ +" at the end of a nez_expression. This expresses a necessary and sufficient condition. Third, there is validation when the Necessary Excitation Zone (NEZ) is validated and when the Facultative Excitation Necessary (FEZ) has been allowed to reach the threshold excitation. The excitation state of the Neuronic depends on the stimulations that the Facultative Excitation Zone receives. The excitation threshold is predefined for each Neuronic. By default, this excitation threshold is equal to 100%. If the excitation threshold is lower than 100%, the system then manages partial information. Note, if the Neuronic is already validated, it cannot be validated again. This corresponds to the notion of the refractory period.



```
$NZ:  "A";
$FEZ: "B" -> 30 and "C" -> 20 -> 65;
      "C" -> 20 and "D" -> 20 -> 30;
```

x and y can be considered as hidden Neuronics

FIGURE 3. Connectivity of Neuronics expressions.

3.6. The Internal Process (IP)

The Internal Process expresses the functional specificity of a Neuronic. There are two ways to do so: the first corresponds to a programming of the Internal Process, the second to the construction of assemblies of Neuronics. Each assembly can be considered as a separate knowledge base.

3.6.1. *Programming of the Internal Process.* The Internal Process allows the description of procedural knowledge having two kinds of actions: the first concerns the outside world (physical environment)—these actions can be produced by either a C function or by an external program. The second type of action concerns the inside world, that is, the knowledge base. These actions will have consequences on the inference process. To program them, communication primitives are used. These primitives will be described below. A special primitive which is not a communication primitive is *state* ("A"). It returns the actual state of the Neuronic "A": undefined, validated, and inhibited.

3.6.1.1. *Action on the outside world.* Everything that is not in the knowledge base network being considered is considered in the outside world. Direct actions on the outside world do not exactly correspond to programming of the Internal Process. They correspond to either call of functions already programmed or to external programs (for example, communication program). It is, therefore, very simple to integrate existing information processing systems into the knowledge base. This allows an open system. There are two aspects to this approach:

- Description of Neuronics which integrate the call of functions into their Internal Process:

$NZ: "NAME OF NEURONIC";
$IP: function "name_of_C_function";

- Programming of the C function. This corresponds to classic C programming.

The description of Neuronics must be stored in an ASCII file and suppose **f** is the file name. The file which contains the programming of the C functions must have the following name: **f_p**, p for programming. These conventions allow MOSAIC, during the compilation of the knowledge base, to compile and link the C function and to establish the link between the Neuronics and the C functions. Note, this approach to using the Internal Process allows the management of functions with a knowledge base.

The first actions on the outside world that the user needs are messages on the terminal. Since, in MOSAIC, everything is Neuronic, these actions are carried out by Neuronics. These basic Neuronics are stored in a knowledge base, called **kernel** base. The functions which produce these actions are programmed in C. They are included in the Internal Processes of Neuronics. Thus, for example, in the cardiac intensive care unit knowledge base, in order to see the Excitation Zone of the Neuronic "DOBUTREX" (cardiac inotropic drug), the physician types **EZ.** This corresponds to the validation of the Neuronic "EZ." The role of the latter's Internal Process is to print the Excitation Zone of the Neuronic "DOBUTREX" on the terminal.

An external program call is similar to a function call.

Example:

```
$NZ:  "KERMIT";
$IP:  function "kermit";
```

and in the function **kermit:**

```
void kermit ();
{
  system ("kermit");
}
```

To summarize, this way of managing functions and programs allows MOSAIC to be an open system, the integration of different kinds of tasks in the same system (task manager) and modularity.

3.6.1.2. *Action on the inside world.* The actions on the inside world influence the inference process. They are based on communication primitives which can change the excitation state of Neuronics. The communication primitives are described below.

3.6.2. *Assemblies of Neuronics: Macro-Neuronic.* The functional specificity of a Neuronic can be defined by an assembly of Neuronics integrated in its Internal Process. The construction of assemblies of Neuronics is based on the recursive definition of the Neuronic (that is, a set of Neuronics can be considered as one Neuronic).

The two parameters necessary to construct an assembly of Neuronics are the convergence-Neuronic from which the construction starts, and the depth level of propagation. The complexity of assembly of Neuronics increases with this depth level. The assemblies where the depth level is equal to 1, correspond to the immediate context of the convergence-Neuronic, that is, to the excitation zones of this Neuronic. When the depth level of propagation is greater than 1, the assembly defines a larger context. An assembly of Neuronics is also a Neuronic, and has the same basic structure including a Necessary Excitation Zone, a Facultative Excitation Zone, an Activation Control Zone, and an Internal Process. To facilitate the description of these zones, the prefix *macro* will be used. The name of the macro-Neuronic corresponds to the name of the class defined by the convergence-Neuronics obtained. At the end of the construction, each zone corresponds to a set of Neuronics. Now, for example, we want to define an assembly of Neuronics having a depth level of propagation equal to n, and we begin the construction with the convergence-Neuronic "X."

3.6.2.1. *Macro Activation Control Zone.* Every Neuronic i which is connected to the Neuronic "X" via $n - 2$ Neuronics belongs to the Macro Activation Control Zone. Every Neuronic j having a common child-Neuronic with a Neuronic i belongs to the Macro Activation Control Zone too. In Figure 4, n is equal to 3. Note, if $n = 1$, the Macro Activation Control Zone and the Excitation Zones are not separated.

3.6.2.2. *Macro Internal Process.* Every Neuronic i which is a child-Neuronic of a Neuronic belonging to the Macro Activation Control Zone, and which is situated at a distance $(1, n - 1)$ from this Neuronic, belongs to the Macro Internal Process.

3.6.2.2. *Convergence-Neuronics.* Every Neuronic i which belongs to the Macro Internal Process is a convergence-Neuronic if it is situated at a distance of $n - 1$ from Neuronics belonging to the Macro Activation Control Zone.

3.6.2.3. *Macro Necessary Excitation Zone.* Every Neuronic i, connected to the Necessary Excitation Zone of a Neuronic belonging to the Macro Activation Control Zone, belongs to the Macro Necessary Excitation Zone. Every atomic Neuronic i, connected to the Necessary Excitation Zone of a Neuronic belonging to the Macro Internal Process, belongs to the Macro Necessary Excitation Zone.

3.6.2.4. *Macro Facultative Excitation Zone.* Every Neuronic i, connected to the Facultative Excitation

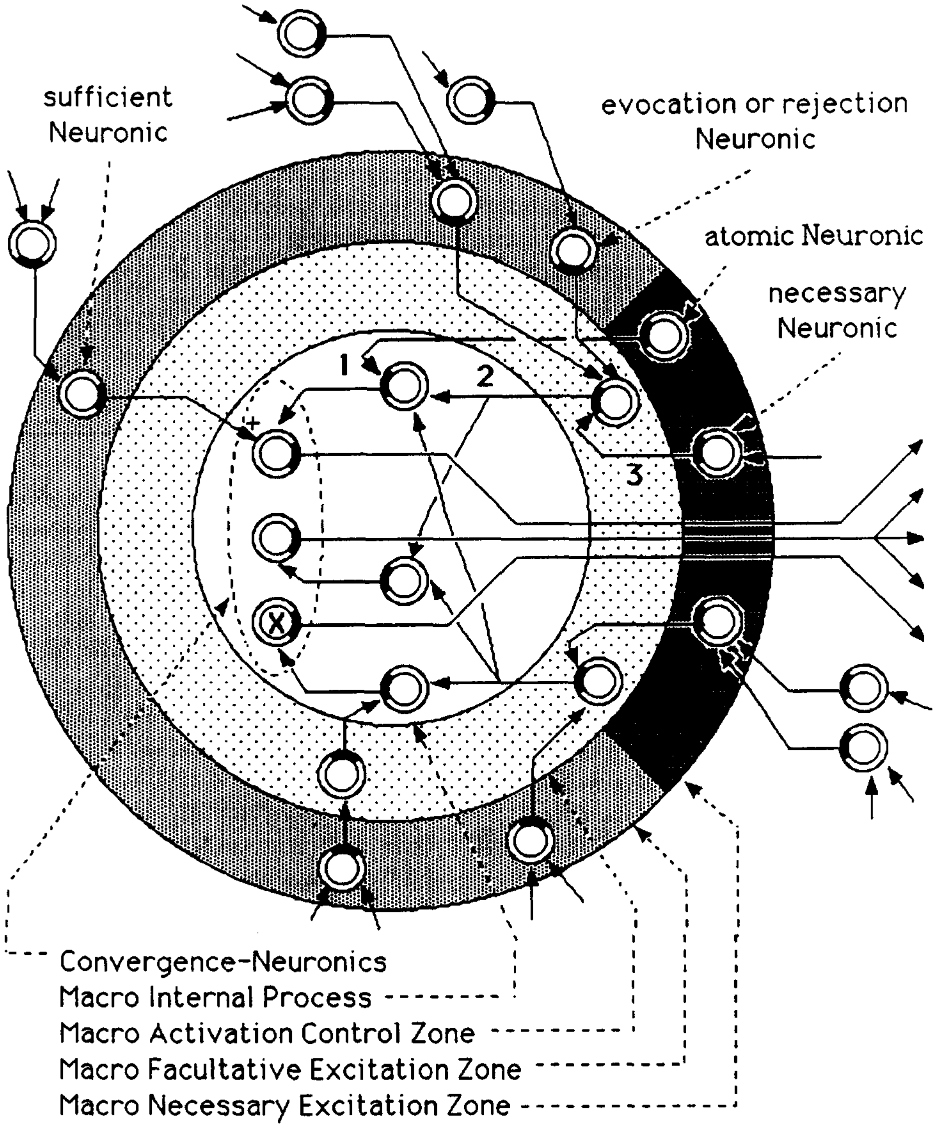


FIGURE 4. An Assembly of Neuronics With a Depth Level of Propagation Equal to 3.

Zone of a Neuronic belonging to the Macro Activation Control Zone, belongs to the Macro Facultative Excitation Zone. Every atomic Neuronic i, connected to the Facultative Excitation Zone of a Neuronic belonging to the Macro Internal Process also, belongs to the Macro Facultative Excitation Zone.

3.6.2.5. *Remarks on the Assemblies of Neuronics.* An assembly of Neuronics is, therefore, defined by five sets of Neuronics: the convergence Neuronics, the Macro Internal Process, the Macro Activation Control Zone, the Macro Facultative Excitation Zone, and the Macro Necessary Excitation Zone. The definition of an assembly of Neuronics corresponds to the definition of the macro-context (or meta-context) which at least allows the validation of one of convergence-Neuronics. The construction of assemblies of Neuronics is interesting in three situations: first, to highlight the organization of a knowledge base; second to emphasize a classification; and third, to allow the definition of the appropriate context of validation of the concepts represented by the convergence-Neuronics. Each assembly of Neuronics can be considered as a knowledge base. These knowledge bases are dynamic since, according to the depth level of the propagation and the convergence-Neuronic, different assemblies of Neuronics can be constructed.

4. COMMUNICATION PRIMITIVES

Connections and communication primitives constitute the mediums of communication between Neuronics. The connections are addressed to the excitation zones. The communication primitives are only used in the Internal Process or in direct commands during a session. Every communication primitive can be used in direct commands, except for the primitive *stimulate*

(). The communication primitives allow the description of procedural knowledge which impacts the inside world, that is, the knowledge-base network, but not the outside world. The communications between entities are general and not semantically linked with the concepts represented by the Neuronics.

- *Validation.* The primitive *validate* ("A") induces an explicit validation of the Neuronic "A." The validation automatically leads to the execution of the Internal Process, if present. MOSAIC subsequently propagates this validation in the network via the connections established between the Neuronics. Propagation can precede the execution of the Internal Process, if explicitly mentioned in the Neuronic "A." If the Neuronic "A" is already validated, or inhibited, *validate* ("A") has no effect.
- *Inhibition.* The primitive *inhibit* ("A") is an explicit order to inhibit the Neuronic "A." If this has been already validated or inhibited, *inhibit* ("A") has no effect.
- *Activation.* The primitive *activate* ("A") is similar to the primitive *validate,* but allows the user to force the change of state of the Neuronic. If the Neuronic "A" was already inhibited, *activate* ("A") will ask the user if he really wants to change the state of the Neuronic "A." If the answer is positive, "A" is validated and its Internal Process, if present, will be executed. If the Neuronic "A" has already been validated, *activate* ("A") will then ask the user to confirm a new validation of the Neuronic "A." If the answer is positive, the Internal Process of the Neuronic "A," if present, will be re-executed. It is, therefore, possible to repropagate the validation of a Neuronic and to execute or to re-execute its Internal Process in a new context.
- *Inactivation.* The primitive *inactivate* ("A") allows the user to force the inhibition of the Neuronic "A."
- *Execution.* The primitive *execute* ("A") systematically leads to a validation and an execution of the Internal Process.
- *Lock.* The primitive *lock* ("A") systematically leads to an inhibition of the Neuronic "A."
- *Validation attempt.* The primitive *try_to_validate* ("A") is an explicit order to start a backward chaining from the Neuronic "A."
- *Activation attempt.* The primitive *try_to_activate* ("A") is similar to the primitive *try_to_validate* ("A"), but during the backward chaining, the system allows the user to force certain changes of state of the Neuronics.
- *Stimulation.* The primitive *stimulate* ("A," w) allows an explicit stimulation of the Neuronic "A." This stimulation is only available during the execution of the Internal Process. When w is positive, a temporary increase in the excitation state occurs, whereas when w is negative, the excitation state of the Neuronic "A" is temporarily reduced. $w \in [-100, 100]$.

5. PROPAGATION AND INFERENCE STRATEGIES

The inference propagation is determined both by the connectivity of the knowledge base network (declarative knowledge) and by the Internal Processes of Neuronics (procedural knowledge). The connections between the Neuronics are bidirectional. Three kinds of inference strategies are accepted: forward chaining, backward chaining, and implicit deduction.

5.1. Forward Propagation and Forward Chaining

Forward chaining corresponds to the *forward propagation* from atomic Neuronics to more complex Neuronics. The control of this propagation depends, on the one hand, on the connectivity of the network and on the other on the excitation state of each Neuronic. The connectivity of the network is established either by explicit descriptions or by learning from examples. The procedural forward chaining is explicitly programmed by the human expert through the communication primitives. According to the declarative or procedural nature of knowledge, a declarative or a procedural chaining mechanism is used.

5.2. Backward Propagation and Backward Chaining

The backward propagation can be explicitly programmed by the human expert or can be spontaneously triggered by the system. To explicitly plan a backward chaining, the human expert must program the Internal Process.

Example:

```
$NZ:  "URETER DILATATION";
$IP:  try_to_validate ("CALCULUS");
```

If the ureter is dilated the system must systematically try to validate a calculus which could be responsible for the obstacle.

However, not every necessary backward chaining can be forecast because it depends on the current context. In MOSAIC, each Neuronic tests its excitation state, and can itself start a backward propagation if this excitation state is close to its threshold excitation, that is, when the Neuronic has an excitation state situated in the interval [80, 100]. Spontaneous activation of backward propagation allows the improvement of the interactions between the user and the system by asking questions at the right time.

The backward chaining is possible because the connections situated on the Facultative Excitation Zone are bidirectional.

5.3. Retropropagation of Necessities and Implicit Deduction

The connections situated on the Necessary Excitation Zone are bidirectional. When a Neuronic is validated, every Neuronic connected to its Necessary Excitation Zone will be validated or inhibited according to the expression defined in this Necessary Excitation Zone. Unlike abduction, this inference process cannot infer wrong conclusions because it uses only information connected to the Necessary Excitation Zone and not to the Facultative Excitation Zone.

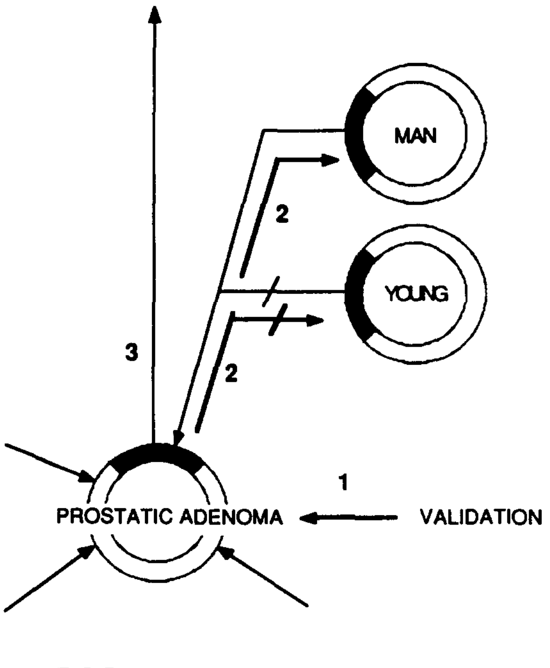
Example:

$NZ: "PROSTATIC ADENOMA";
$NEZ: "MAN" and ! "YOUNG";
$FEZ: . . .

In this example, if the Neuronic "PROSTATIC ADENOMA" is validated; this implicitly means that the patient is a man who is not young (Figure 5). This corresponds to an implicit deduction.

6. KNOWLEDGE BASE CONSTRUCTION

MOSAIC allows the following kinds of knowledge acquisition in a single system: explicit knowledge acquisition, which corresponds to descriptions of declarative and procedural knowledge, and knowledge acquisition based on learning from examples. Several knowledge bases can be merged.



$NZ: "PROSTATIC ADENOMA";
$NEZ: "MAN" and ! "YOUNG";
$FEZ: ...

FIGURE 5. Example of a Retro-Propagation of Necessities.

The acquisition of declarative knowledge corresponds to the creation of the connectivity of the knowledge base network and the creation of connection weights. The connectivity of the knowledge network constitutes the knowledge base skeleton. The establishment of connection weights completes the construction of the knowledge base. *Connection weight $W(i, j)$ represents either an evocation or a rejection strength between a Neuronic i and a Neuronic j.* When knowledge is acquired by the explicit transfer from the human expert, the calculation of connection weight can be expressed in terms of the *reliability* and of the *specificity* of information. When knowledge is acquired by the learning from examples, the calculation corresponds to a measure of relative impacts a Neuronic has on its child-Neuronics.

Procedural knowledge is described in the Internal Processes and corresponds to a programming of this zone. See the section "The Internal Process (IP)" for more details.

6.1. Explicit Knowledge Acquisition

The explicit description of a knowledge base corresponds to the description of its Neuronics. One concept is not fragmented into several rules as in rule-based systems, but corresponds to a Neuronic. This allows a modular description of the knowledge base.

6.1.1 *Methodology for the Explicit Definition of a Neuronic.* Two kinds of Neuronics can be distinguished according to the excitation zones. The first kind is *atomic Neuronics*, that is, Neuronics representing concepts considered atomic. Their excitation zones are empty. They are automatically generated by the system when the excitation zones are analyzed. They do not need to be explicitly defined, except when synonyms are created or when an atomic Neuronic is only mentioned in an Internal Process. The second kind have connections attached to their excitation zones. In both cases, the Internal Process may or may not be defined according to whether there is or there is not a procedural knowledge attachment to the concept represented by the Neuronic.

6.1.1.1. *Explicit Necessary Excitation definition.* There are a number of questions which can guide the creation of the Necessary Excitation Zone: What conditions are absolutely necessary (not mandatorily sufficient) for the validation of a given Neuronic? Another is: What concepts, that is, Neuronics, must be implicitly validated or inhibited if a given Neuronic is validated? This question expresses the *retro-propagation of necessities* described above.

6.1.1.2. *Explicit Facultative Excitation Zone definition.* The question which can guide the creation of the Facultative Excitation Zone is: What principal elements evoke or reject the concept represented by a given Neuronic? The Facultative Excitation Zone is not an exhaustive list of evocation or rejection elements. The experience of the human expert will select the most vaulable elements.

6.1.2. *Application: Explicit Medical Knowledge Acquisition.* There are several kinds of medical concepts including symptom, syndrome, pathology, test, and therapy concepts.

6.1.2.1. *Symptoms.* Symptoms represent the lowest conceptual level in a medical knowledge base. They are represented by atomic Neuronics. The excitation zones are not useful because symptoms are atomic concepts. The Internal Process is not necessary either because usually there is no systematic medical process for a given symptom. In medicine, information must be associated with the context; isolated it has practically no sense.

6.1.2.2. *Syndromes.* A syndrome corresponds to an association of symptoms which defines a particular context having a particular physiopathologic significance (for example, nephrotic syndrome). When a physician validates a given syndrome, he implicitly validates all signs which constitute the syndrome. In MOSAIC, this process corresponds to the retropropgation of necessities. The Neuronics which constitute the definition of the syndrome are connected to the Necessary Excitation Zone of the syndrome-Neuronic. The Neuronics which have only an evocation or a rejection role are connected to the Facultative Excitation Zone. The following example shows that a Neuronic does not only define a concept but, in addition, it takes the local context into account where this concept can be validated. The medical definition of the nephrotic syndrome includes proteinuria and hypoalbuminemia. Edema and hypercholesterolemia are frequently present.

Example:

```
$NZ: "NEPHROTIC SYNDROME";
$NEZ: "PROTEINURIA" and "HYPOALBUMIN-
EMIA" → +;
$FEZ: "EDEMA" → 50;
  "HYPERCHOLESTEROLEMIA" → 30;
  . . .
```

In this example, the Neuronics "PROTEINURIA" and "HYPOALBUMINEMIA" define the Neuronic "NEPHROTIC SYNDROME," since they represent necessary elements (connections to the NEZ), and sufficient elements (→ +). The Neuronics "EDEMA" and "HYPERCHOLESTEROLEMIA" are connected to the Facultative Excitation Zone since they are evocation elements for the syndrome. With this representation, the three kinds of inference strategies will act as follows:

- If the physician has observed that the patient is suffering from proteinuria and hypoalbuminemia, this will validate the Necessary Excitation Zone of the Neuronic "NEPHROTIC SYNDROME." This validation is necessary, since it concerns the Necessary Excitation Zone, and it is sufficient, since the qualifer (→ +) has been used. This corresponds to a simple deduction.
- If the physician validates directly the Neuronic "NEPHROTIC SYNDROME," a retropropagation of necessities will be automatically triggered (that is, implicit deductions). If there is a nephrotic syndrome then there is, by definition, a proteinuria and a hypoalbuminemia.
- If the physician has only observed that the patient has edema and hypercholesterolemia, this information must evoke a nephrotic syndrome to trigger questions on the existence of a proteinuria and of a hypoalbuminemia in the patient. If the physician validates the Neuronics "EDEMA" and "HYPERCHOLESTEROLEMIA," the excitation state of the Neuronic "NEPHROTIC SYNDROME" is increased to 80% (50 + 30). At this excitation level, MOSAIC considers the Neuronic "NEPHROTIC SYNDROME" relevant and attempts to validate it. It highlights this Neuronic, and asks the physician whether or not the patient has a proteinuria and an hypoalbuminemia. If the answer is positive, the Neuronic "NEPHROTIC SYNDROME" will be validated.

6.1.2.3. *Pathology.* Pathology diagnosis consists of the evaluation of different elements of evocation, rejection, and confirmation. These elements are connected to the Facultative Excitation Zone of the pathology. The connection weight is positive for an evocation, negative for a rejection, and sufficiently positive for a confirmation element. Usually the latter is not connected to the Necessary Excitation Zone since it is only considered as a sufficient element and not a necessary and sufficient one. Medical decisions are often made under risk, the physician being unable to wait for confirmation before starting a treatment. However, there are some classes of pathology where diagnostic confirmation is absolutely necessary (for example, antimitotic drugs). In these cases, the confirmation element (e.g., histologic diagnosis) is connected to the Necessary Excitation Zone with a sufficiency connection weight.

The following example using only evocation elements is extracted from the cardiac intensive care knowledge base developed by Dr. B. Abry at the Broussais University Hospital:

Example:

```
$NZ: "TAMPONADE";
$FEZ: "ORTHOPNEA" → 80;
  "EVOCATION OF TAMPONADE WITH ECHOGRAPHY" → 75;
  "RADIOGRAPHIC CARDIOMEGALY" → 70;
  "RIGHT HEART FAILURE" → 50;
  "OLIGURIA" → 50;
  "IMMEDIATE IMPORTANT POST-OPERATIVE HEMORRHAGE" → 50;
  "RELATIVE AUGMENTATION OF CREATINEMIA" → 50;
  "RECENT ABLATION OF DRAINAGE TUBE" → 45;
  "RECENT ABLATION OF ELECTRODES" → 40;
  "PERIPHERAL SHOCK STATE" → 40;
  "EPIGASTRALGIA" → 35;
  "VOMITING" → 35;
```

6.1.2.4. *Tests.* Tests have indications and contraindications. Neuronics which correspond to absolute indications (for example, gastroscopy for a hematemesis) have an absolute positive stimulation intensity on the Facultative Excitation Zone. The other indications are represented by Neuronics connected to the Facultative Excitation Zone with positive stimulation intensities. Neuronics representing absolute contraindications are connected to the Necessary Excitation Zone. Relative contraindications are represented by Neuronics connected to the Facultative Excitation Zone with negative stimulation intensities.

Example:

```
$NZ: "INTRAVENOUS UROGRAPHY";
$NEZ: ! "KIDNEY FAILURE" and ! "ALLERGY TO THE CONTRAST MEDIUM";
$FEZ: "REPERCUSSIONS ANALYSIS OF RENAL ARTERY STENOSIS" → +;
  . . .
```

In this example, the absolute contraindications are represented by Neuronics "KIDNEY FAILURE" and "ALLERGY TO THE CONTRAST MEDIUM." The sign "+" at the end of the fez_expression expresses the sufficiency of information.

6.1.2.5. *Therapies.* Therapies are described with their indications and contraindications.

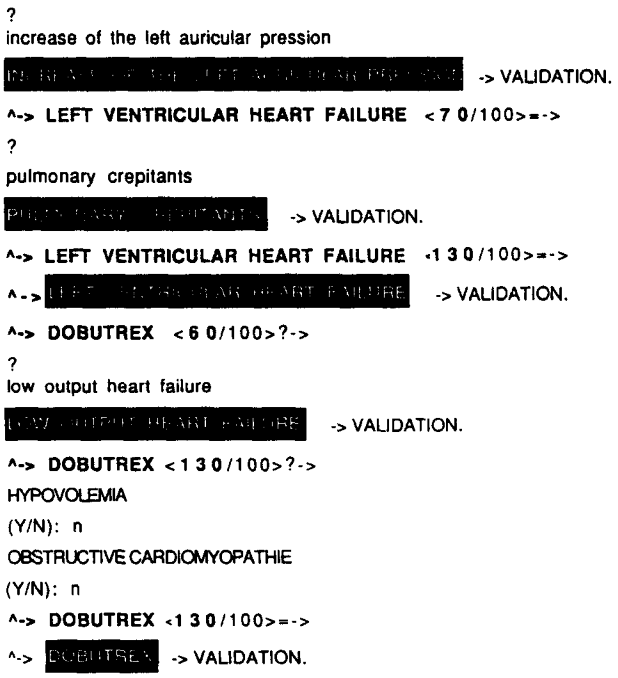
Example:

```
$NZ: "DOBUTREX";
$NEZ: ! "HYPOVOLEMIA" and ! "OBSTRUCTIVE CARDIOMYOPATHY";
$FEZ: "LOW OUTPUT HEART FAILURE" → 70;
  "BRADYCARDIA" → 60;
  "ATRIOVENTRICULAR HEART FAILURE" → 60;
  "PULMONARY HYPERTENSION" → 60;
  "PERIPHERAL VASOCONSTRICTION" → 60;
  "HYPOTENSION" → 60;
  "LEFT SIDED HEART FAILURE" → 60;
$IP: printf("DOSE: 5 to 20 microgramme/kg/mn.");
  printf("USE:  Rectify the metabolic acidosis,");
  printf("      don't dilute with a basic solution,");
  printf("      inject continuously with an electrical syringe.");
  printf("PRECAUTION FOR USE: when there is cardiac rhythm failure.");
```

Absolute contraindications of drugs are connected to the Necessary Excitation Zone. In this example, the Neuronic "DOBUTREX" can only be validated if there is no contraindication (that is, inhibition of Neuronics "HYPOVOLEMIA" and "OBSTRUCTIVE CARDIOMYOPATHY" as shown in Figure 6).

6.2. Learning From Examples

A new algorithm for the unsupervised learning from examples is proposed. It is termed Estimated Connection Weights Learning. This algorithm takes the different excitation zones into consideration. It is a fast algorithm because it performs estimations and uses simple calculations. In MOSAIC, there are two processes during the learning period: the first is the construction of excitation zone, the second is the update and storage of the necessary parameters for the calculation of connection weights. These two processes are simultaneously conducted. The learning is unsupervised, that is, the system does not need error corrections.



```
?
increase of the left auricular pression
INCREASE OF THE LEFT AURICULAR PRESSION  -> VALIDATION.
^-> LEFT VENTRICULAR HEART FAILURE  <7 0/100>=->
?
pulmonary crepitants
PULMONARY CREPITANTS   -> VALIDATION.
^-> LEFT VENTRICULAR HEART FAILURE  <1 3 0/100>=->
^-> LEFT VENTRICULAR HEART FAILURE   -> VALIDATION.
^-> DOBUTREX  <6 0/100>?->
?
low output heart failure
LOW OUTPUT HEART FAILURE   -> VALIDATION.
^-> DOBUTREX <1 3 0/100>?->
HYPOVOLEMIA
(Y/N): n
OBSTRUCTIVE CARDIOMYOPATHIE
(Y/N): n
^-> DOBUTREX <1 3 0/100>=->
^-> DOBUTREX  -> VALIDATION.
```

FIGURE 6. Example of the Validation of a Drug in Trace Mode.

Examples are presented to MOSAIC as an ASCII file. A medical diagnosis application, CLASSi corresponds to a pathology, and Si to a sign. Any number of signs can be given. Each case is presented to the system as a Nominal Zone (name of pathology diagnosed) associated with a list of signs present in this case ($EX means signs presented for learning from examples). The following format is used:

Learning_case ::=
  $NZ: "CLASSi";
  $EX: {"Si";} . . .

6.2.1. *Construction of Neuronics by Learning From Examples.* The construction of Neuronics by learning from examples corresponds to the construction of their excitation zones. When the first case is presented, for every concept present in this case (that is, CLASS1, S1, S2, S3) a Neuronic is created: "CLASS1," "S1," "S2," "S3." During the presentation of the case, every Neuronic Si is connected to the Necessary Excitation Zone of the Neuronic "CLASS1" (Figure 7). They constitute a conjunctive expression connected to the Necessary Excitation Zone. The Facultative Excitation zone is empty. When the second case is presented, the Neuronics which were present in the first case and are absent in the second case ("S3" in the example), are disconnected from the Necessary Excitation Zone and connected to the Facultative Excitation Zone. The new concepts appearing in the presentation of the second case lead to the creation of new Neuronics ("S4" and "S5" in the example) which are directly connected to the Facultative Excitation Zone and constitute a conjunctive expression, that is, a fez_expression (Figure 7). Often at the end of learning, the fez_expressions are reduced to a single Neuronic. The process described above is repeated for each case presented. If the number of examples presented is less than 50, the Necessary Excitation Zone is considered not significant and the Neuronic connected to the Facultative Excitation Zone.

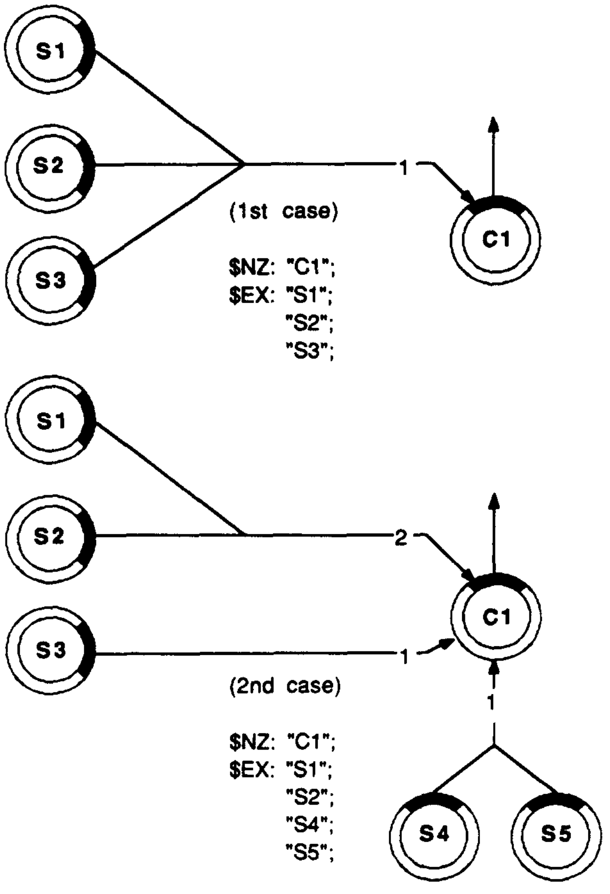


FIGURE 7. Construction of the Excitation Zones During the Learning From Examples.

6.2.2. *Learning Parameters.* The creation of these parameters is automatically determined by MOSAIC. The *learning connection weights are a comparative measure of information impact.* The basic idea expressed in the formula for their calculation is to evaluate the impacts of a Neuronic on its child-Neuronics. After the period of learning from examples, the system has stored a number of necessary parameters for the calculation of connection weights:

- $N(E_j | c_k)$: The number of cases where the Neuronic_expression E_j was present when the class k was present. In the knowledge base network this class is represented by a Neuronic designated c_k.
- $N(n_i)$: The number of cases where the Neuronic n_i was present during the learning period. n_i is a Neuronic representing a sign Si.
- $N(c_k)$: The number of cases where the class k was present during the learning period.
- N: The total number of cases presented to MOSAIC during the learning period.
- *Nb_Class*: The number of classes presented to MOSAIC.

Each parameter defined above is automatically determined by the system during the period of learning from examples. The evaluation of the impact of E_j with regard to each class c_k is based on a comparative process. The connection weight $W(E_j, c_k)$ is calculated as follows:

$$W(E_j, c_k) = \frac{P(E_j | c_k)}{\pi(E_j)} \tag{7}$$

where $P(E_j | c_k)$ is the probability of E_j when c_k is present and $\pi(E_j)$ is the estimated probability of E_j.

$$P(E_j | c_k) = \frac{N(E_j | c_k)}{N(c_k)} \tag{8}$$

$$\pi(E_j) = P(E_j | c_k) + (\pi(E_j | \overline{c_k}) * (Nb\_Class - 1)) \tag{9}$$

where $\pi(E_j \mid \overline{c_k})$ is the estimated probability of E_j when the class is not c_k.

$$\pi(E_j \mid \overline{c_k}) = \frac{(min\{N(n_i)\} - N(E_j \mid c_k))}{(N - N(c_k))} \qquad (10)$$

where n_i is a Neuronic belonging to the Neuronic_expression E_j.

To avoid taking irrelevant information into account, a *significance threshold* is defined as follows:

$$Significance\_Threshold = max \begin{cases} \dfrac{100}{Nb\_Class} + Standard\_Deviation \\ Parasite\_Threshold \end{cases} \qquad (11)$$

where *Standard_Deviation* and *Parasite_Threshold* are arbitrary constants, respectively, equal to 2 and 10. The final value of the connection weight is calculated as follows:

$$W(E_j, c_k) = \begin{cases} 0 \text{ if } W(E_j, c_k) \leq \text{Significance\_Threshold} \\ W(E_j, c_k) \text{ otherwise.} \end{cases} \qquad (12)$$

The significance threshold allows the system to avoid information which is always present in all classes and also parasite information which has an excessively low connection weight. Note, this calculation does not correspond to a calculation of probabilities. $\pi(E_j)$ is an estimated value, it is not the probability of E_j (that is, $P(E_j)$). Indeed, the formula of $P(E_j)$ would be:

$$P(E_j) = \frac{\sum_{k=1}^{Nb\_Class} N(E_j \mid c_k)}{N}. \qquad (13)$$

In the present case, this calculation has no sense because E_j can represent a combination of signs, and not to a single sign.

7. APPLICATION TO THE DEVELOPMENT OF MEDICAL EXPERT SYSTEMS

MOSAIC has been initially applied to the development of medical expert systems. The medical domain represents an interesting area for the implementation of knowledge-based systems due to the complexity of medical concepts and the wide variety of reasoning processes. Medicine is an inexact science and the recognition of diseases is a context-dependent problem, in which each sign must be interpreted according to the clincial history of the patient. Situations in which a single sign can give the diagnosis (that is, a *pathognomonic* sign) are exceptions. In addition, the context does not correspond to an exhaustive list of signs, it is a combinatory set where each sign is not absolutely necessary nor it has the same strength of evocation or rejection. Medical reasoning must be able to process partial, uncertain, and imprecise information.

MOSAIC has already been used to develop a knowledge base on rejection after kidney transplantation (Pham & Degoulet, 1989). The purpose of this development was to test the feasibility of the approach and the validity of the concepts. MOSAIC, with new features, is now being used to develop two expert systems where the knowledge base is explicitly constructed: the first concerns the decision to hospitalize and the selection of investigations according to the cardiac risk factors presented by the patient (hypertension, tobacco, hypercholesterolemia, diabetes, age, . . .). At present, the knowledge base contains 141 Neuronics with 117 connections. We have integrated into this knowledge base two others (27 Neuronics): the kernel knowledge base and an elementary common sense knowledge base. The second expert system is devoted to the domain of cardiac intensive care. It concerns the management of therapeutic decisions in a cardiac intensive care unit. The knowledge base is composed of 159 Neuronics with 141 connections. The first positive results of the development of these two expert systems are the ease of the knowledge transfer and of the modification of the knowledge bases and the efficiency of the management of drugs according to their indications and contraindications (for example, see Figure 6). Every medical example cited in this article comes from these two expert systems. Another knowledge base was developed to test the efficiency of learning from examples implemented in MOSAIC. It concerns the hypertension domain. Currently, MOSAIC is being used to construct a knowledge base on the etiologies of hypertension. Two hundred-seventeen cases were fed to MOSAIC which were extracted from the database ARTEMIS (Devriès et al., 1987) which contains 20,000 patients suffering from hypertension.

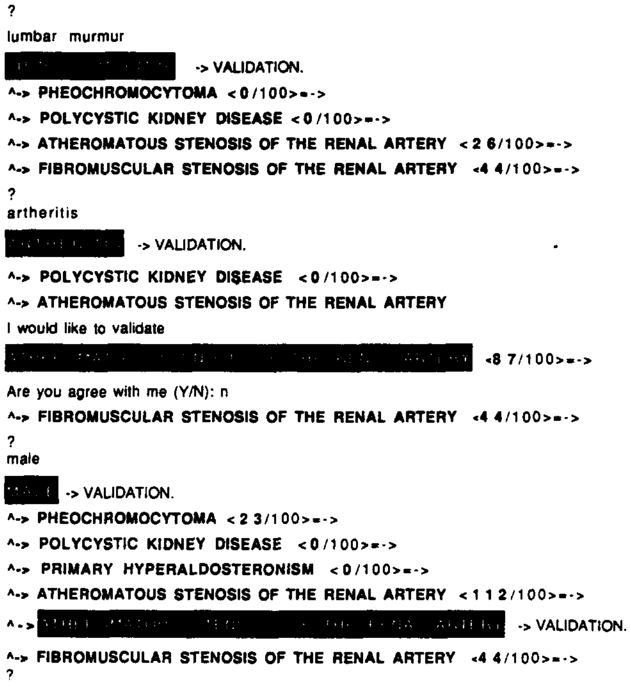
The diagnostic categories presented to MOSAIC were: PHEOCHROMOCYTOMA (30 cases), POLYCYSTIC KIDNEY DISEASE (39 cases), ATHEROMATOUS STENOSIS OF THE RENAL ARTERY (81 cases), FIBROMUSCULAR STENOSIS OF THE RENAL ARTERY (46 cases), and PRIMARY HYPERALDOSTERONISM (21 cases). One hundred-eight Neuronics were created, and 329 connections were established. The learning was effected on a Micro Vax III. The CPU time for learning was less than 1 second.

The signs associated to the diagnoses were elements of the standard medical check-up for hypertension. The physician can evoke diagnoses with these signs. The following well known medical contexts were rediscovered by MOSAIC (for example, see Figure 8) after the learning period:

- Hypertension + Headaches + Palpitations + Sweating evoke PHEOCHROMOCYTOMA.
- Hypertension + Lumbar murmur + Atheritis + Man + evoke an ATHEROMATOUS STENOSIS OF THE RENAL ARTERY.
- Hypertension + Lumbar murmur + Atheritis + Man evoke an ATHEROMATOUS STENOSIS OF THE RENAL ARTERY.
- Hypertension + Hypokalemia evoke a PRIMARY HYPERALDOSTERONISM.
- . . .

8. DISCUSSION AND CONCLUSION

MOSAIC constitutes a new ANN approach. It differs from the connectionist approach by the functional organization level. This level, termed the macro-connectionist level, allows the management of more complex and structured knowledge in a general numerical communication network. The MOSAIC approach is based on three principal features: *the numerical connectivity aspect,* the *autonomous functional structured entities,* and the possibility of *recursive construction of assemblies of entities.* The numerical connectivity allows the integration of a number of connectionist concepts, in particular learning from examples, partial and uncertain information processing and an efficient information propagation mechanism. The learning from examples, proposed in MOSAIC, is unsupervised and it allows rapid learning because the algorithm can estimate and MOSAIC is not a full-connected network. The functional structured entities allow the representation of complex knowledge and their autonomy the construction of a modular knowledge base. Recursive construction of assemblies of Neuronics represents a new perspective for the management of knowledge bases including the emergence of classes and the auto-organization of knowledge bases.



```
?
lumbar  murmur
[redacted]  -> VALIDATION.
^-> PHEOCHROMOCYTOMA <0/100>=->
^-> POLYCYSTIC KIDNEY DISEASE <0/100>=->
^-> ATHEROMATOUS STENOSIS OF THE RENAL ARTERY  <2 6/100>=->
^-> FIBROMUSCULAR STENOSIS OF THE RENAL ARTERY  <4 4/100>=->
?
artheritis
[redacted]  -> VALIDATION.
^-> POLYCYSTIC KIDNEY DISEASE  <0/100>=->
^-> ATHEROMATOUS STENOSIS OF THE RENAL ARTERY
I would like to validate
[redacted]  <8 7/100>=->
Are you agree with me (Y/N): n
^-> FIBROMUSCULAR STENOSIS OF THE RENAL ARTERY  <4 4/100>=->
?
male
[redacted] -> VALIDATION.
^-> PHEOCHROMOCYTOMA <2 3/100>=->
^-> POLYCYSTIC KIDNEY DISEASE  <0/100>=->
^-> PRIMARY HYPERALDOSTERONISM  <0/100>=->
^-> ATHEROMATOUS STENOSIS OF THE RENAL ARTERY <1 1 2/100>=->
^->[redacted] -> VALIDATION.
^-> FIBROMUSCULAR STENOSIS OF THE RENAL ARTERY  <4 4/100>=->
?
```

FIGURE 8. Inference Process of a Knowledge Base Constructed by Learning From Examples.

A number of important differences between MOSAIC and traditional knowledge-based systems must be stressed. There is a distinction between excitation zones and the left-hand members of production rules. The left-hand member of a production rule expresses the condition for the validation of that rule. *Neuronic excitation zones* express the context for the validation of that Neuronic. The context constitute combinations of factors which can define different possible conditions of validation.

The connection weights, contrary to the certainty factors, have only a local action. Each of them is only used in the calculation of the excitation state of one Neuronic. Another difference between connection weights and certainty factors is the facility of modulating the connection weights with reliability coefficients. *Often, Neuronics are compared with the objects.* However, they differ by the absence of a mandatory classification and by the absence of the notion of messages. In MOSAIC, communications are based on the numerical connectivity, and communication primitives. The latter are general primitives such as validate or inhibit. Moreover, Neuronics are not a list of attributes, but correspond to the creation of a context of validation. Neuronics are threshold units, there is a notion of validation which does not exist with the objects.

The MOSAIC approach is unlike usual connectionist expert systems, because it allows different strategies of inference (forward chaining, backward chaining, and implicit deduction), the management of structured complex information and the processing of both declarative and procedural knowledge. In connectionist systems, the inference propagation mechanism is unidirectional, since the connection between two units is single and oriented. These systems can, therefore, only have one kind of reasoning strategy, that is, forward chaining. In "classical" and connectionist expert systems, knowledge acquisition can be explicit and/or realized by learning from examples. Partial and uncertain information can be processed in a natural way thanks to the numerical propagation mechanism and to threshold entities. During one session, several diagnoses can be established since the propagation mechanism is carried out by the whole network. The maintenance of the coherence of the knowledge base is facilitated by the notion of the refractory period and by the remarks produced by the system when an activated Neuronic becomes inactivated and vice versa. In MOSAIC, there are two levels of adaptation for reasoning: one is global, and the other is local. The Neuronic network constitutes a dynamic knowledge base because the validation of a Neuronic is the result of the current global excitation state of the network. This global excitation state defines the context of inference. It is dynamically determined. Therefore, there is a continual adaptation of reasoning to the global context. The local level of adaptation is defined by the excitation zones and by the Internal Processes. When a Neuronic has received a number of stimuli on its excitation zones, it can itself trigger a backward chaining process which was not explicitly defined by the human expert. This allows the generation of adapted questions to the user. The Internal Process allows the human expert to describe procedural knowledge corresponding to a specific situation represented by the relevant Neuronic in question.

MOSAIC is an open system developed with the C programming language. This choice was motivated by the efficiency, generality, and portability of this programming language. So, every C environment can be easily integrated into MOSAIC. The Internal Processes of Neuronics are C functions—they are compiled with a C compiler. Unlike usual connectionist systems, MOSAIC allows a natural integration of any existing computer science systems via the Internal Processes. The latter can include any kind of process (communication program, request to a database, etc). MOSAIC can manage different kinds of processes because the Communication and Activation Envelope constitutes an interface for numerical inference propagation.

However, the limits of the MOSAIC approach and the future development required should be stressed. *The first limit is the memory.* Indeed, for each validation of Neuronic there is a propagation in the network. This propagation can trigger new validations and propagations, and so on. Memory overflow can, therefore, occur. In practice, the depth of propagation does not exceed 3. However, it should be possible to fix the depth of propagation. At present, *Quantitative information* is represented by C global variables. For each knowledge base, there is an associated file containing the declarations of these variables. This solution is probably not definitive, the number must be integrated with attributes. The management of attributes and the variable binding must be implemented in the short term. Another area for possible extensions is the user interface. This can be subdivided into two aspects: The quality of the list of synonyms which allows a better semantic interaction, and the quality of presentation (windows, mouse, . . .) which allows a better physical interaction with the user (Barsalou, 1989). X window system with MOTIF will be the software environment for the development of the graphic interface. We will, therefore, have a very portable system (C and X window system). Another objective of MOSAIC is to manage the interactions between the signal and the symbol levels with the sames structures. The recursive definition of Neuronics allows the construction of progressive layers between the perception level and the symbol level. Another solution is the encapsulation of a technology of signal processing, for example, "classical" technology or connectionist systems. However, this constitutes a completely new area of research.

REFERENCES

Barsalou, T. (1989). An object-based architecture for biomedical expert database systems. In *Proceedings of the Twelfth Annual Symposium on Computer Applications in Medical Care* (pp. 572–578). Washington, DC: IEEE Computer Society Press.

Booker, L.B., Goldberg, D.E., & Holland, J.H. (1989). Classifier systems and genetic algorithms. *Artificial Intelligence*, **40**(1–3), 235–282.

Carbonell, J.G. (1989). Special volume on machine learning. *Artificial Intelligence*, **40**(1–3).

Carew, T.J. (1987). Cellular and molecular advances in the study of learning in aplysia. In J.P. Changeaux and M. Konishi (eds.), *The neural and molecular bases of learning* (pp. 177–204). New York: Wiley-Interscience.

Changeux, J.P. and Dehaene, S. (1989). Neural models of cognitive functions. Cognition, 33(1–2), 63–109.

Changeux, J.P. & Konishi, M. (1987). The neural and molecular bases of learning. In J.P. Changeux and M. Konishi (Eds.), *Report of the Dahlem Workshop 1985*. New York: Wiley-Interscience.

Delacour, J. (1987). *APPRENTISSAGE ET MEMOIRE, une Approche Neurobiologique*. Masson.

Devriès, C., Degoulet, P., Jeunemaitre, X., Chatellier, G., Aimé, F., et al. (1987). Integrating management and expertise in a computerized system for hypertensive patients. *Nephrol Dial Transplant*, **2**, 327–331.

Dudai, Y. (1987). Rapporteur group report: On neuronal assemblies and memories. In J.P. Changeux and M. Konishi (eds.), *The neural and molecular bases of learning* (pp. 503–539). New York: Wiley-Interscience.

Eimas, P.D. & Galaburda, A.M. (1989). Neurobiology of cognition. *Cognition*, **33**(1–2), 1–23.

Elman, J.L. & Zipser, D. (1987). Learning the hidden structure of speech. In *ICS Report* 8701, Institute of Cognitive Science (UCSD).

Fogelman-Soulié, F., Cornuejols, A., Gallinari, P., Le Cun, Y., & Thiria, S. (in press). Network learning. In Y. Kodratoff and R.S. Michalski, (eds.), *Machine Learning, Vol. III*.

Fukushima, K. (1988). Neocognitron: A hierarchical neural network capable of visual pattern recognition. *Neural Networks*, **1**, 119–130.

Gallant, S.I. (1988). Connectionist expert systems. *Communications of the ACM*, **31**(2), 152–169.

Hendler, J.A. (1989). Marker-passing over microfeatures: Towards a hybrid symbolic/Connectionist model. *Cognitive Science*, **13**(1), 79–106.

Hinton, G.E. (1989). Connectionist learning procedures. *Artificial Intelligence*, **40**(1–3), 185–234.

Holland, J.H. (1973). Genetic algorithms and the optional allocation of trials. *SIAM J. Comput.* **2,** 88–105.

Kandel, E.R., Abrams, T., Bernier, L., Carew, T.J., Hawkins, R.D., & Schwartz, J.H. (1983). Classical conditioning and sensitization share aspects of the same molecular cascade in Aplysia. *Cold Spring Harbor Symposium on Quantitative Biology,* **48,** 821–830.

von der Malsburg, C. (1987). Synaptic plasticity as basis of brain organization. In J.P. Changeux and M. Konishi (eds.), *The neural and molecular bases of learning* (pp. 411–431). New York: Wiley-Interscience.

Pham, K.M. & Degoulet, P. (1988). MOSAIC: A macro-connectionist organization system for artificial intelligence computation. *Proceedings of the IEEE-ICNN,* **II,** 533–540.

Pham, K.M. & Degoulet, P. (1989). MOSAIC: Medical knowledge processing based on a macro-connectionist approach to neural networks. *Proceedings of MEDINFO,* **I,** 82–86.

Pfeifer, R., Schreter, Z., Fogelman-Soulie, F., & Steels, L. (1989). *Connectionism in perspective.* New York: Elsevier.

Saito, K. & Nakano, R. (1988). Medical diagnostic expert system based on PDP model. *Proc. IEEE-ICNN,* **I,** 255–262.

Schank, R.C. and Colby, K.M. (1973). *Computer models of thought and language.* San Francisco: Freeman.

Sejnowski, T. & Rosenberg, C. (1987). NETL talk: A parallel network that learns to read aloud. *Computer Systems,* **1,** 145–168.

Shastri, L. (1988). A connectionist approach to knowledge representation and limited inference. *Cognitive Science* **12,** 331–392.

Touretzky, D.S. & Hinton, G.E. (1988). A distributed connectionist production system. *Cognitive Science,* **12,** 423–466.

Touretzky, D.S. & Pomerleau, D.A. (1989, August). What's hidden in the hidden layers? *BYTE,* 227–233.

APPENDIX

Conventions

The conventions for the description of Neuronics are:

[ ]	Optional indications.
{ }...	The elements between the brackets can be repeated *n* times.
→ *W*	Indicates a stimulation with a connection weight *W*.
→ +	Indicates a sufficient validation stimulation of a Neuronic.
→ −	Indicates a sufficient inhibition stimulation of a Neuronic.

The conventions during a session with MOSAIC are:

?	MOSAIC is ready, it waits information.
^→	Indicates a propagation.
⟨ES/ET⟩?→	Indicates the excitation state (ES) and the threshold excitation (ET). The element "?" indicates that the Necessary Excitation Zone has not been evaluated.
⟨ES/ET⟩ = →	The element "=" indicates that the Necessary Excitation Zone is validated or empty.
⟨ES/ET⟩|→	The element "|" indicates that the Necessary Excitation Zone has already been evaluated and it cannot be validated.