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Variable Oscillation Frequencies for Solving the Problem of Multiple Instantiation

Jacques Sougné
Department of Psychology
University of Liège
4000 Liège, Belgium
J.Sougne@ulg.ac.be

Abstract

Distributed connectionists models of reasoning must solve the problem of multiple instantiation for two reasons. First, reasoning can involve two or more instantiations of the same predicate or object. Second, in a distributed representation, two closely related concepts must share common resources or nodes. Reasoning with these two concepts requires that nodes pertaining to them be instantiated twice. This paper presents a model (INFERNET) that uses temporal synchrony variable binding. It proposes a particular solution to the problem of multiple instantiation that involves the use of different oscillation frequencies. This solution implies some predictions. These predictions are tested on human participants, and the results are presented here. They confirm model predictions.

Introduction

Multiple instantiation involves the simultaneous use of the same parts of the knowledge base in different ways. Knowing that "John is in love with Rita" and that "Rita is in love with John", you can easily infer that they should be happy. To arrive at that conclusion you had to instantiate the predicate "is in love with" and the objects "John" and "Rita" twice. Precisely how this is done, especially in distributed systems, is the problem of multiple instantiation.

Models that load copies of pieces of knowledge into a working area before transforming them do not have any problem with multiple instantiation. They simply make several copies of the same content from the Long Term Knowledge Base. However, for connectionists models that use the structure of the knowledge base itself as the place where concepts are associated, transformed and where inferences are drawn, multiple instantiation is a serious problem. How can the same part of the knowledge base be associated with different things at the same time without making several copies of the knowledge in question? This question is crucial for connectionist models of working memory and reasoning. Multiple instantiation is an even greater problem for distributed representations. Two closely related concepts will, at least in principle, have some parts or nodes in common. If these two concepts are needed at the same time, their common parts must be instantiated twice.

The connectionist model of reasoning presented here, INFERNET, implements a working memory that is the activated part of long term memory. This is achieved by making use of temporal properties of the node spikes. A particular solution of the problem of multiple instantiation is proposed. This model makes predictions that have been tested experimentally and the results of these experiments are reported here. These results challenge modular models of memory.

Temporal synchrony variable binding systems

Systems that achieve variable binding through temporal synchrony attempt to solve the binding problem through the use of temporal properties of node firing. In short, when one node fires in synchrony with another, they are temporarily bound together. This technique is successfully able to represent *n-ary* predicates. This idea has been successfully applied to "reflexive" reasoning (Shastri & Ajjanagadde, 1993), to natural language parsing (Henderson, 1994), to analogical inferences (Hummel & Holyoak, 1996), and to deductive reasoning (Sougné, 1996).

INFERNET description

Concepts and attributes

INFERNET is a connectionist model whose nodes employ an integrate-and-fire principle. Each concept is represented by a cluster of nodes firing in synchrony (figure 1). Concepts can be bound together by the same type of synchrony. For example, to represent the concept "red rose", nodes belonging to "red" should fire in synchrony with nodes belonging to "rose" (figure 1). There is neurobiological evidence for considering synchrony as a possible binding mechanism in the brain. In particular, this phenomenon has been observed between distant cells in the same cortical area (Gray, König, Engel & Singer, 1989), between cells in different cortical areas (Eckhorn, Bauer, Jordan, Brosch, Kruse, Munk & Reitboeck, 1988) and even between cells in different hemispheres (Engel, König, Kreiter & Singer, 1991). Engel, König, Gray & Singer (1990) have shown that individual cells can rapidly change partners of synchrony. Moreover the absence of synchronization has been observed to impair abilities (Lowell & Singer, 1992).

Discrimination

Discrimination is achieved by successive synchronies, for example, to discriminate a red rose on a green lawn. The nodes belonging to "red" and "rose" must fire in synchrony and those corresponding to "green" and "lawn" must fire in synchrony, but these two sets of nodes must fire in succession in order to be distinguished (figure 1). Engel, Kreiter, König & Singer (1991) provide evidence that shows that if several objects are present in a scene, several group of cells are grouped in distinct windows of synchrony.

First constraints

A number of neurobiological parameters are involved in this type of representation. The first is the frequency of oscillation. In INFERNET, as in SHRUTI (Shastri & Ajjanagadde 1993), once a node is activated, it tends to fire rhythmically at a frequency of from 30 to 100 Hz. The temporal gap between 2 spikes of a node is therefore from 10 to 33 ms. Certain types of neurons oscillate at a frequency of 30 to 100 Hz (γ wave). These γ waves have been observed to be associated with attention (Wang & Rinzel, 1995) and with associative memory (Wilson & Shepherd, 1995). Both attention and associative memory are required by reasoning. The second parameter is the precision of the synchrony. This precision is about 5 ms (Abeles & al., 1993).

Windows of synchrony

How are successive synchronies differentiated? SHRUTI uses the activation of special kind nodes (τ-and nodes) that indicate boundaries of the rhythmic oscillation of predicates, and thereby, the limits of synchronies. INFERNET, on the other hand, uses the *distribution* of node-firing times. Since concepts are represented by a set of nodes, we focus on when firing occurs. If the firing distribution is tightly concentrated about the mean, the concept is considered to be activated. In Figure 1, nodes corresponding to the concept "rose" are firing in synchrony and the firing time distribution is concentrated around the mean. Nodes pertaining to "rose" fire in synchrony with nodes representing "red". This synchrony is distinguished from the synchrony between nodes pertaining to "green" and "lawn". Their means are clearly different.

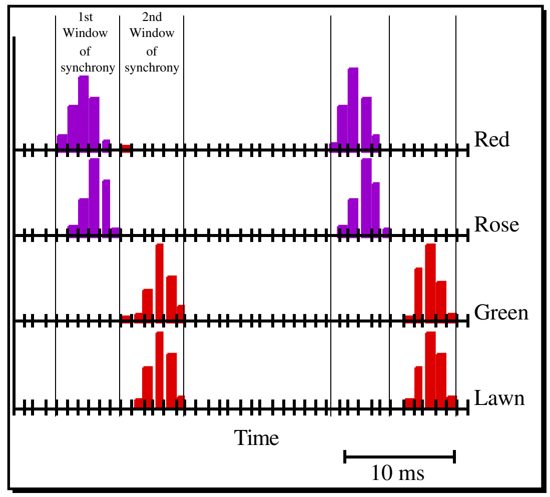

Figure 1: The "red rose on the green lawn" requires binding of concepts "red" and "rose", succeded immediately by "green" and "lawn".

Predicates

Predicates and arguments are represented by successive synchronies. To represent "Mary is taller than Georges", we need the abstract relation **IS-TALLER (p, q)** and we must bind "Mary" to **p** and "Georges" to **q**. We also need 3 successive windows of synchrony: the first contains "is-taller", the second contains "p" and "Mary", and the third contains "q" and "Georges".

Deductive inferences

Deriving inferences requires the addition and replacement of synchronies. For example from *"Mary is taller than Georges"* and *"Georges is taller than Barbara"*, the system should be able to conclude that *"Mary is taller than Barbara"*. Figure 2 shows the binding of the predicate arguments and the adding and replacement of synchronies. This is achieved by a set of excitatory and inhibitory links, by a set of presynaptic amplification and inhibition links, and by delays assigned to connections. A complete description of the structure of links and delays can be found in Sougné (in preparation). Note that transitions between sequences require more steps than are represented in the Figure 2.

When the system receives a question, it must bind the instantiated arguments to the generic arguments in the rule. In the first premise of the previous example, “Mary” must be bound to **p**, “Georges” to **q**, and “Barbara” to **r**. So, when the rule derives the conclusion, activation is transmitted to the instantiated arguments. This causes them to fire in synchrony with the argument slots of the rule. In Figure 2, “Mary” is bound to **p**, “Georges” to **q** and “Barbara” to **r**. When the rule infers that **p** is taller then **r**, **p** and **r** must be correctly bound to “Mary” and “Barbara”. This requires a form of learning, an adjustment of connection strengths and transmission delays. In INFERNET, this is achieved by a Hebbian learning rule.

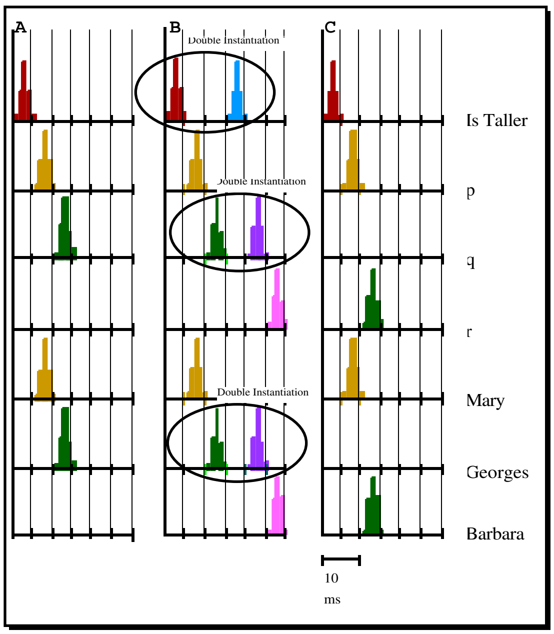

Figure 2: Bindings of the query content to the rule slots and replacement by the sequence representing transitive inference. A: Representation of the fact: Is-taller (Mary, Georges); every concept is instantiated once. B: Representation of the facts: Is-taller (Mary, Georges) and Is-taller (Georges, Barbara). Is-taller, q and Georges are instantiated twice. C: Representation of the transitive inference: Is-taller (Mary, Barbara)

Maintenance of working memory

How can this representation be maintained in working memory? The problem with γ waves is that they persist only a few hundred milliseconds. This is not long enough to reflect the time taken by people to draw inferences, nor does it correspond to standard estimates of working memory retention time (10 to 20 seconds). For this reason, following Lisman & Idiart (1995), γ waves in INFERNET are nested inside θ waves [3 - 7 Hz] whose duration can exceed 10 seconds. The resulting pattern consists of a bursting wave nested in a longer wave. The resulting temporal firing pattern for a single node is shown in Figure 3. There is neurobiological evidence for this rhythm in working memory. θ waves have been observed to be associated with working memory tasks (Nakamura, Mikami & Kubota, 1992). The node shown fires at 50 Hz for the seven spikes that constitutes a burst. This is followed by a resting period of 60 ms. Thereafter, the burst begins again. The burst interval is about 200 ms (5 Hz).

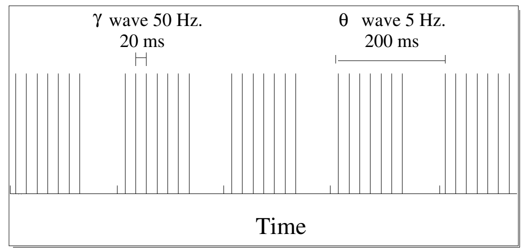

Figure 3: γ wave nested in θ wave

Multiple instantiation

To complete the model, we need a mechanism able to do multiple instantiation. As mentioned in the introduction, models that load copies of parts of Long Term Memory content into a Working Memory buffer can equally well make one or many copies of the same content. However, a model that does not employ this loading process and views Working Memory as the active part of Long Term Memory, must still be able to do multiple instantiation. Mani & Shastri (1993) use a set of copies of the predicate and its argument slots. In their model, SHRUTI, activation is directed to an uninstantiated copy by a switch. SHRUTI predicts that the time for propagating multiple instantiation is proportional to the number of copies. However, this prediction seems contradicted by some experimental data.

Some experimental data shows that at least double instantiation is handled without any problem by human participants. Clark (1969) studied the performance of participants with transitive inference. His data reveal no difference in processing time between problems with doubly instantiated predicate and problems with singly instantiated predicates. In other words, this would seem to imply that there is, in fact, no cost in terms of additional processing time for double instantiation. This property will emerge naturally from the underlying assumptions of INFERNET.

The present model modifies the frequency of the γ wave to enable multiple instantiation. This means that neurons pertaining to a concept doubly instantiated will oscillate twice as fast as singly instantiated ones. The double instantiation of the predicate "is taller" and the objects "Georges" and "q" is illustrated in Figure 2.

If we assume a γ wave frequency between 30 and 100 Hz., *multiple instantiation should be limited around 3 with little or no additional cost for the system.* While some nodes could fire at 30 Hz., double instantiated ones could fire at 60 Hz., and triple instantiated at 90 Hz. Our model suggests also that the brain does multiple instantiation by replacing a number of windows of synchrony by a single "chunked" one. If the number of instantiations exceeds 3, there will be an increase of processing time whose increase will be proportional to the difficulty of "chunking".

Sougné (1996) (experiment 2) proposed a relational reasoning task to human participants. The first group of participants received these premises:

"Allan is in love with Mary",
"Mary is in love with Allan",
"Peter is in love with Barbara",
"Barbara is in love with Peter".

The second group received these premises:

"Peter is in love with Mary",
"Barbara is in love with Allan",
"Allan is in love with Mary"
"Mary is in love with Peter".

After reading these premises, participants had to infer which people were happy (i.e. where their love was reciprocated). A higher proportion of subjects gave the correct answer in the first group where relations are all reciprocal (.92), than in the second group (.66). Response times for correct responses were also significantly shorter for the first group (mean: 3719 ms) than for the second (mean: 7778 ms).

For the first group where all relations are reciprocal, subjects can rapidly replace the relation "is in love with" by "love each other", and finally, by "are happy", therefore reducing the number of instantiations. By contrast, in the second group, subjects need to distinguish items for which the "love each other" relation is true from items for which this relation is false and maintain this distinction in working memory, before enabling the replacement process. This additional process takes time, explaining the significantly higher responses.

This experiment shows that constraints on the replacement process impair cognitive abilities. It also shows that at least double instantiation is handled efficiently, because the replacement process in this experiment involves simultaneously using at least two instantiations of concepts. For example: "Mary is in love with Allan" and "Allan is in love with Mary" must be considered simultaneously to be replaced by "Allan and Mary love each other".

For a distributed connectionist model, multiple instantiation should also affect related concepts. Concepts that share properties most likely share something in the neurobiological substrate. The effect of multiple instantiation should be observable when related concepts are used together. The following experiment tests this hypothesis.

Experiment

In a distributed connectionist model, a single concept is represented by a large set of nodes. In INFERNET a concept is represented by a set of nodes firing in synchrony. The distributed nature of each concept implies that closely related concepts have some nodes in common. If in an episode of reasoning, two related concepts are needed and if they cannot belong to the same window of synchrony, the nodes that they share must be instantiated twice. In the present experiment the number of closely related concepts was manipulated. The prediction was that if the number of instantiations of shared properties exceeded 3, a replacement process would be triggered. This replacement must take time and would be reflected in the subjects' response time.

Participants and design

The 40 subjects were undergraduate psychology majors. They were randomly assigned to each of two conditions. These two conditions differed in the amount that the concepts used in the experiment shared common properties.

Material

Two rules of the type A⊃B (material implication), one for each condition, were constructed. These rules have the same length. The first rule involved rather distant concepts: "If the lumberjack cuts down the oak tree, the farmer's tractor can use the pathway". The second rule used more closely related concepts: "If the lumberjack cuts down the oak tree, the carpenter can nail the oak boards". In the latter rule, there are 7 concepts related to wood. Four questions for each condition were designed. For the first condition: "The lumberjack cut down the oak tree. What do you conclude?" "The lumberjack didn't cut down the oak tree. What do you conclude?" "The farmer's tractor can use the pathway. What do you conclude?" "The farmer's tractor can't use the pathway. What do you conclude?"

For the second condition: "The lumberjack cut down the oak tree. What do you conclude?" "The lumberjack didn't cut down the oak tree. What do you conclude?" "The carpenter can nail the oak boards. What do you conclude?" "The carpenter can't nail the oak boards. What do you conclude?"

The four questions and the rule correspond to the following logical forms: A⊃B, A; A⊃B, ~A; A⊃B, B; A⊃B, ~B. All material was presented by a computer program allowing response times to be recorded. Participants' conclusions were recorded manually.

Procedure

Each participant was facing the monitor. One of the rules appeared on the screen. Participants were asked to read the rule and to indicate when they had understood it. The rule stayed on the screen during the entire experiment. Questions appeared on the screen, one at the time and in random order. Participants had to answer each question while the computer recorded the reaction time. Before presenting the experimental material, participants received training exercises with the same procedure, but with an arithmetic content.

Results and discussion

There was a highly significant difference of mean reaction time for equivalent responses on answering the first question presented (Mann-Whitney Z = 2.994, p= 0.002). The mean for the first group was 3499 ms. and for the second group 4893 ms. All other differences of reaction time were not significant.

There is no difference for subjects reading one rule or another, but when they receive the first question, they must encode the rule in a particular way permitting the inference to be drawn. This encoding requires dealing with multiply instantiated properties that share the concepts used in the rules. A replacement process is required, "the lumberjack cuts down the oak tree" must be assigned to a unique antecedent object, or window of synchrony. The two different consequents: "The farmer's tractor can use the pathway" and "The carpenter's helper can nail the oak boards" must also be assigned to a single consequent object or window of synchrony. For this consequent part there is a difference: concepts in the sentence: "The carpenter's helper can't nail the oak boards" share properties with each other and with those used in the antecedent part of the rule. Multiple instantiations of these shared properties impair the replacement process and the time for answering the question increases. When next questions appear, this replacement has already been solved, and the reaction times are no longer different. The reaction time difference for the first question is not due to the type of question that is seen. The four different questions appear in random order for each participant and there is no significant differences in reaction time between the two groups for each of the inference drawn A, ~A, B and ~B. The only difference between the two groups occurs for the *first* question - when encoding occurs.

There is another fact that reinforces the idea that the only difference between groups involves multiple instantiation. There is no difference of frequency between groups related to the conclusions inferred.

INFERNET predicts that multiple instantiation does not require additional processing time as long as the number of instantiations does not exceed 2 or 3. This prediction is confirmed by the results of Clark (1969) and challenge SHRUTI's prediction that processing time is proportional to the number of instantiated objects. When the number of instances exceeds 2 or 3, INFERNET predicts a replacement process which requires additional processing time. INFERNET also predicts that dealing with closely related concepts will require multiple instantiation. The results of the present experiment confirms this hypothesis. These results would seem to support distributed concept representations and challenge modular accounts of memory. For these models (e.g. Baddeley, 1986), Working Memory is separated from Long Term Memory and the contents of LTM are loaded into WM when needed. According to modular memory models, multiple instantiation must not increase reaction time. The results reported here contradict this prediction.

Conclusions

For connectionist models of reasoning that do not separate Working Memory from Long Term Memory, the problem of multiple instantiation is a serious one.

The model presented here, INFERNET, is a temporal synchrony variable binding model that uses multiple oscillation frequencies to solve the problem of multiple instantiation. Nodes instantiated twice oscillate twice as fast as singly instantiated nodes. The model predicts multiple instantiations to be limited to 2 or 3 before an increase in processing time is observed. When more than 2 or 3 instantiations are needed, INFERNET replaces the bindings of a pair of multiply instantiated objects, with a single chunked one. This replacement process increases processing time. INFERNET also predicts the same effect for closely related concepts.

Experimental data have been presented that would seem to confirm INFERNET's predictions.

Experimental data presented here would also seem to challenge modular accounts of long term memory and working memory. These models suppose that copies of the long term memory content are loaded into working memory. These models predict no cost in processing time for multiple instantiation. The results presented here show, on the contrary, that multiple instantiation of concepts or parts of concepts, does have a cost in processing time when the number of instantiations exceeds a threshold of two or three.

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