The Neural Proposition: Structures for Cognitive Systems

Michael S. P. Miller
Los Angeles, California USA
piagetmodeler@hotmail.com

Abstract

Cognitive structures are the foundation of Jean Piaget's Genetic Epistemology. Yet the elusive question remains: "What are Piaget's cognitive structures?" and more importantly, "How can they be represented computationally?" Piaget described the monad as an immaterial, weightless, dimensionless entity, while he referred to a scheme as both process and structure. This paper explores an approach to combining the notions of monad and scheme to create a simple knowledge representation. Building upon the work of several authors, notably Jean Piaget, Ryszard Michalski, and Roland Hausser, the neural proposition is the central cognitive structure of the PAM-P2 cognitive system.

"The central idea is that knowledge proceeds neither solely from the experience of objects nor from an innate programming performed in the subject, but from successive constructions, the result of constant development of new structures." ~ Jean Piaget

Introduction

Jean Piaget viewed the formation of knowledge as a continual process of construction. In his view, cognitive structures are synthesized, integrated and differentiated ad infinitum. To realize this process, this paper proposes a simple knowledge representation (see Fig. 1). Using this representation a cognitive system such as PAM-P2 can model its environment, and construct knowledge.

PAM-P2 is a cognitive architecture (see Fig. 12). Starting from a minimal set of reflexes and prioritized needs, a robot or device connected to PAM-P2 should be able to think about and react to its environment, make attempts to satisfy needs, consider the possible effects of actions before executing them (i.e., perform mental simulation), create analogical, deductive, and inductive inferences, and improve its solutions over time.

PAM-P2 is influenced by: database semantics (Hausser 2010); dynamic interlaced hierarchies (Heib and Michalski 1993; Tecuci and Michalski 1993; Alkharouf and Michalski 1996) behavioral schemas (Drescher 1991); ontology formation (Indurkhya 1992); temporal activation (Miller 2011); micro theories (Lenat and Guha 1990); and cognitive system patterns (Miller 2012a).

PAM-P2 was designed expressly to perform observation, coordination, regulation, and compensation according to definitions set forth in Piaget (1978; 1985). As a result, while building its world model PAM-P2 should achieve and maintain equilibrium by continually regulating (i.e. correcting or reinforcing) solutions for needs and compensating (reversing or neutralizing the effects of) solution failures. The model that PAM-P2 constructs is a database of neural propositions.

The PAM-P2 system is psychologically inspired by the work of Jean Piaget. There is also biological evidence for some features of the system. Recently, Yamakawa (2012) has proposed that the hippocampus performs scheme generation and scheme storage in the brain by projecting schemes onto the neocortex. This finding aligns the hippocampus with the PAM-P2 scheme generators (the coordination components) and the scheme storer.

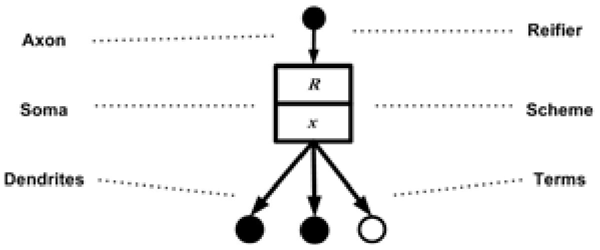


Figure 1. The neural proposition.

A neural proposition is a logical proposition that exchanges activation with its terms. A comparison can be made between the dendrites of a biological neuron and the terms of a logical proposition. Also, a neural proposition has a reifier which functions as a biological axon. Finally, the proposition's activation is time-based to facilitate decay.

In practice, a neural proposition consists of two fundamental structures: monads (constants), mental representations of entities in the world, and schemes (predicates), relations among monads.

Monads

Gottfried Leibniz thought of monads as metaphysical atoms while Jean Piaget conceived them to be immaterial, dimensionless entities. For our purposes, a monad is a representation of a concept, residing within or outside a cognitive system. In the cases where a monad represents a purely internal concept with no external correlate, it is said to be a "newly synthesized" concept (Drescher 1991).

From a logical perspective, a monad is a constant. Visually a monad is represented by a dot. A monad has an activation (which can be On, Off , or Void), a numerical rank (to place it within a heterarchical plane), and a numerical tier (to place it on a particular plane among many).

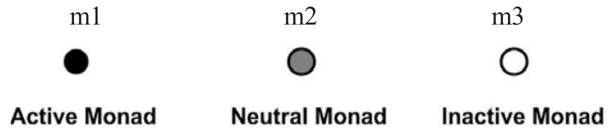


Figure 2a. A monad has an activation and can be active (enabled or "On"), neutral (i.e., "Void"), or inactive (impeded or "Off"). This figure shows three monads, m1, m2 and m3.

Observables, Coordinations, and Facts

As a representation of an external entity, a monad is said to represent what Piaget calls an "observable". "An observable is anything that can be established by immediate experience of the facts themselves" (Piaget 1985). "An observable is that which experience makes it possible to identify by an immediate reading of the given events themselves."(Piaget 1978).

We will call that which we perceive directly, observables. This will include all sensory stimuli. Inferences arising from observables are called "coordinations".

In the PAM-P2 system, both observables and coordinations are referred to as "facts". And all facts are represented by monads. A fact represents a condition that may be enabled or impeded. An active monad is enabled, an inactive monad is impeded. A neutral monad is void (or dormant), it is not a fact.

Goals

Often a monad's activation is required to achieve or maintain a necessary condition. When such is the case, a monad becomes a goal of the PAM-P2 system. Goals may be Open, Satisfied, or Expired. A monad which becomes a goal immediately has a disposition of Open. If a monad becomes a fact while it is an open goal, the goal disposition changes to Satisfied.

All goals have a predetermined expiration. The expiration may be established and extended by various processes, but eventually if a goal remains open beyond its allotted timeframe, the disposition of the goal will change to Expired.

Dyads

A dyad is a pair of monads that have contrary activation with respect to one another (Fig 3b). When one monad is enabled, the other monad in the dyad is impeded, and vice versa. One monad in a dyad, is the thesis monad and represents the proposition, while the other monad, the antithesis, represents the negated proposition. For convenience a dyad is visualized as a circle filled half with black and half with white (Fig. 3c) to indicate the contrary activation. Jean Piaget indicated that it is necessary for a cognitive system to have as many positive characteristics as negative characteristics: "…this means that there will be as many negations as affirmations. Sometimes the correspondence between them remains implicit, but often it must be made more or less explicit" (Piaget 1985, p.9).

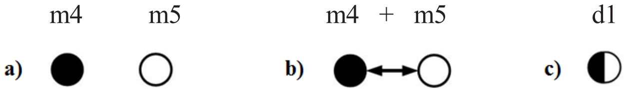


Figure 3. Monads forming a dyad.

Schemes

Relations

A logical relation consists of a predicate and arguments. For example, the relation ***R(x, y)*** has the predicate ***R*** and arguments ***x*** and ***y***. In PAM-P2 there is also a meta-relation ***RELATION*** which defines relations. For example, ***RELATION(R, x, y, z)*** means that ***R(x,y,z)*** forms a relation.

There are two kinds of relations, internal and external. Internal relations are synthesized by PAM-P2's inferential processes acting upon the model. The following are examples of "internal relations" in the PAM-P2 system:

UNISON(x)
SERIES(x)
SAME(x, y)
CASE(x, y)
EXPECT(x, y, z)
OPTION(x)
DIFFERENT(x, y)
SIMILAR(x, y)
TYPE(x, y)
PREDICT(w, x, y, z)

External relations fall into three basic categories (percepts, urges, and effects), and are asserted and activated (or impeded) by sensor, receptor, and actuator processes outside the PAM-P2 cognitive system.

Schemes

Jean Piaget used the word scheme to refer either to a strategy, an abstract cognitive structure, or a specific action. It is the second sense, scheme as cognitive structure, which is relevant here. He described the scheme as a flexible entity which can undergo: assimilation and accommodation. Assimilation is the incorporation of elements foreign to a scheme into the scheme. This author proposes that the "foreign elements" that schemes assimilate are monads, so, assimilation means adding a monad to a scheme. Accommodation is the process of modifying schemes. More accurately, to accommodate a scheme means to copy it and then modify the copy by inserting or deleting monads.

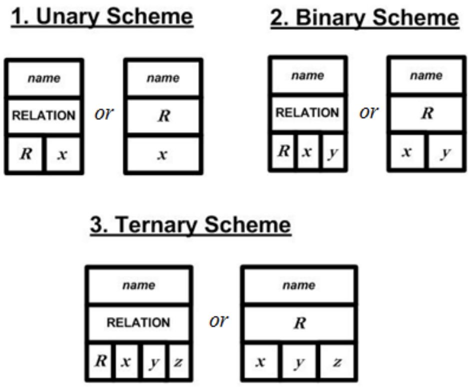
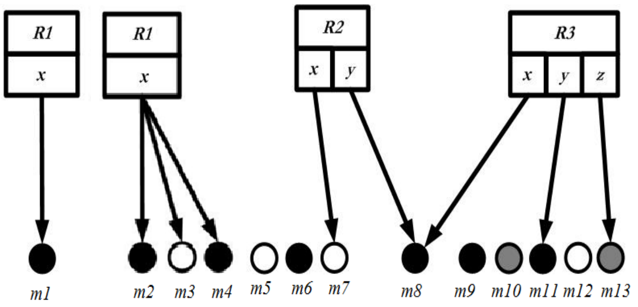


Figure 4. Unary, binary, and ternary schemes.

A computational scheme is a structure that characterizes an instance of a relationship among monads. The relationship may be unary, binary, ternary, (see Fig. 4) or n-ary. A computational scheme consists of a name (which is optional), a relation, and terms (which are required).

Terms

Each scheme has fillers called "terms" which function in much the same manner as do terms in logical propositions. Each term may be either an individual monad or a collection of monads (representing disjunctions, conjunctions, sequences, or cycles).



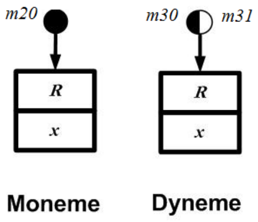
R1(m1)
R1({m2, m3, m4})
R2(m7, m8)
R3(m8, m11, m13)

Figure 5. Four schemes.

Reifiers, Monemes, and Dynemes

In addition to schemes having monads as terms, monads may also represent entire schemes. A scheme is reified when a monad is used to represent the scheme. Reifiers reside on a higher tier than the scheme terms. In PAM-P2 system the lowest tier is perception, and therefore monads on the lowest tier represent sensory stimuli. As the tier increases, monads are reified and become more abstract.

When a single monad reifies a scheme, this combination is called a "Moneme". When a dyad reifies a scheme, the combination is called a "Dyneme".



m20: R({})

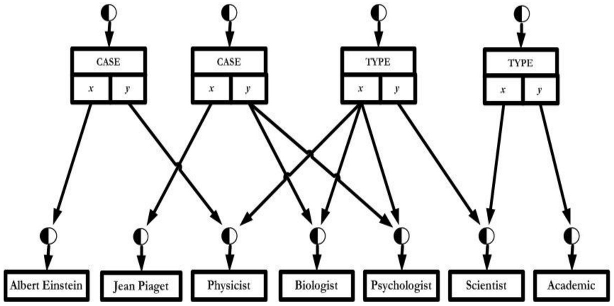
$$d1\begin{cases} m30: R(\{\}) \\ m31: \neg R(\{\}) \end{cases}$$

Figure 6. The graphical and logical representation of a moneme and a dyneme. Monemes and Dynemes are neural propositions.

Monemes vs. Frames

A frame is a data structure that is often used to represent an object or concept. The attributes of a frame are called "slots" and the values of those attributes are called fillers. Collections of frames are organized in a hierarchical taxonomy or ontology. Frame systems typically support the inheritance inference technique while other inference techniques may be provided by daemons, i.e., functions attached to slots. On the other hand, monemes participate in a variety of inference techniques beyond inheritance and they do not use daemons.

A generalization taxonomy usually takes the form of a hierarchical diagram using frames. With monemes, a generalization taxonomy would occur within a specific tier (see Fig.7).

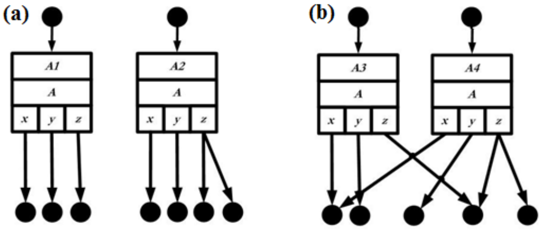


d1: "Albert Einstein".
d2: "Jean Piaget".
d3: "Physicist".
d4: "Biologist".
d5: "Psychologist".
d6: "Scientist".
d7: "Academic".
d8: CASE(d1, d3).
d9: CASE(d2, {d4, d5}).
d10: TYPE({d3,d4,d5}, d6).
d11: TYPE(d6, d7).

Figure 7. A generalization taxonomy.

Integration and Differentiation

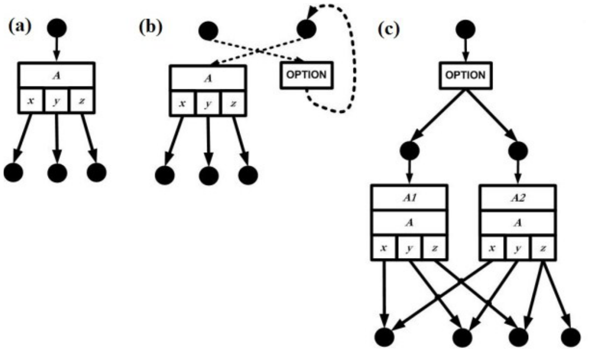
Monemes facilitate integration (see Fig. 8) and differentiation (see Fig. 9). With any neural proposition the underlying scheme will change over time. The moneme (or dyneme) can be differentiated or integrated while maintaining its identity through its monad interface.



(a) m4: A(m1, m2, m3) as "A1".
m9: A(m5, m6, {m7, m8}) as "A2".

(b) m10: A(m1, m2, m7) as "A3".
m11: A(m1, m3, {m7, m8}) as "A4".

Figure 8. Monemes m4 and m9 are integrated by cloning them to form m10 and m11, and then modifying the clones.



(a) m4: A(m1, m2, m3).

(b) m4: OPTION(m5).
m5: A(m1, m2, m3).

(c) m4: OPTION({m5, m6}).
m5: A(m1, m2, m3) as "A1".
m6: A(m1, m2, {m3, m7}) as "A2".

Figure 9. (a) A moneme, m4, holding relationship A is differentiated into sub-schemes A1 and A2, by (b) inserting an OPTION relationship indicating a choice between (c) the original form of the scheme, now denoted A1, and the new form A2 (Piaget 1985).

Activation

By using activation and salience, candidate monads are selected to participate in various inferential processes.

Activation Flow

An argument within a relation can be afferent, where activation flows from the argument into the relation, or efferent, where activation flows from the relation to the argument. The flow of an argument is defined by the relation. For example, the UNISON relation has one argument which is afferent. The TYPE relation has two arguments (subclass, superclass), the first of which is afferent while the second is efferent. This means that for the TYPE relation, activation flows into the first argument and out of the second argument.

Term Activation and Merge Types

A term has an activation of "On", "Off", or "Void" much in the same way that monads have. The activation of a term is determined by the merge type of the scheme's relation. There are six basic merge types: PASS[through], NOT, AND, OR, NAND, NOR (see Fig. 11). Each merge type defines how activation for afferent monads in a term is propagated to the scheme's reifier. When all afferent terms of a scheme are activated according to the merge type, then the scheme is activated. Once a scheme is activated, efferent terms and the reified monad(s) are then activated.

Moments

For cognitive systems using neural propositions time is measured in moments—a unit of time equal to 3.1556 milliseconds. In PAM-P2 the function *Now( )* returns the current moment. For example, the moment 2015500505050000 is circa the date 1 July 2015 at 12:30:30 pm. A moment can represent either a specific time point or a duration. For example 3 seconds in duration is approximately 1000 moments.

Activation Window

The PAM-P2 system maintains a specific configuration parameter called the "Activation Window" which identifies the duration that a monad is considered to be activated or inhibited. Subtracting the Activation window from *Now( )* yields the Activation Threshold.

$$\mathit{ActivationThreshold} = \mathit{Now}(\,) - \mathit{ActivationWindow} \qquad (1)$$

Any monads activated or inhibited before the Activation Threshold are considered to be in a void state.

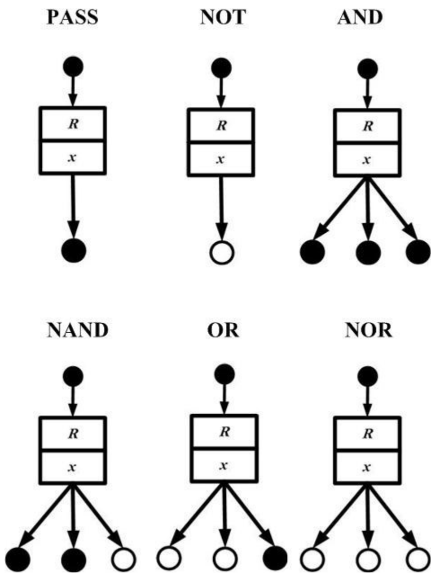


Figure 11. The activations of the afferent term monads are passed up to the reified monad according to the scheme's merge type.

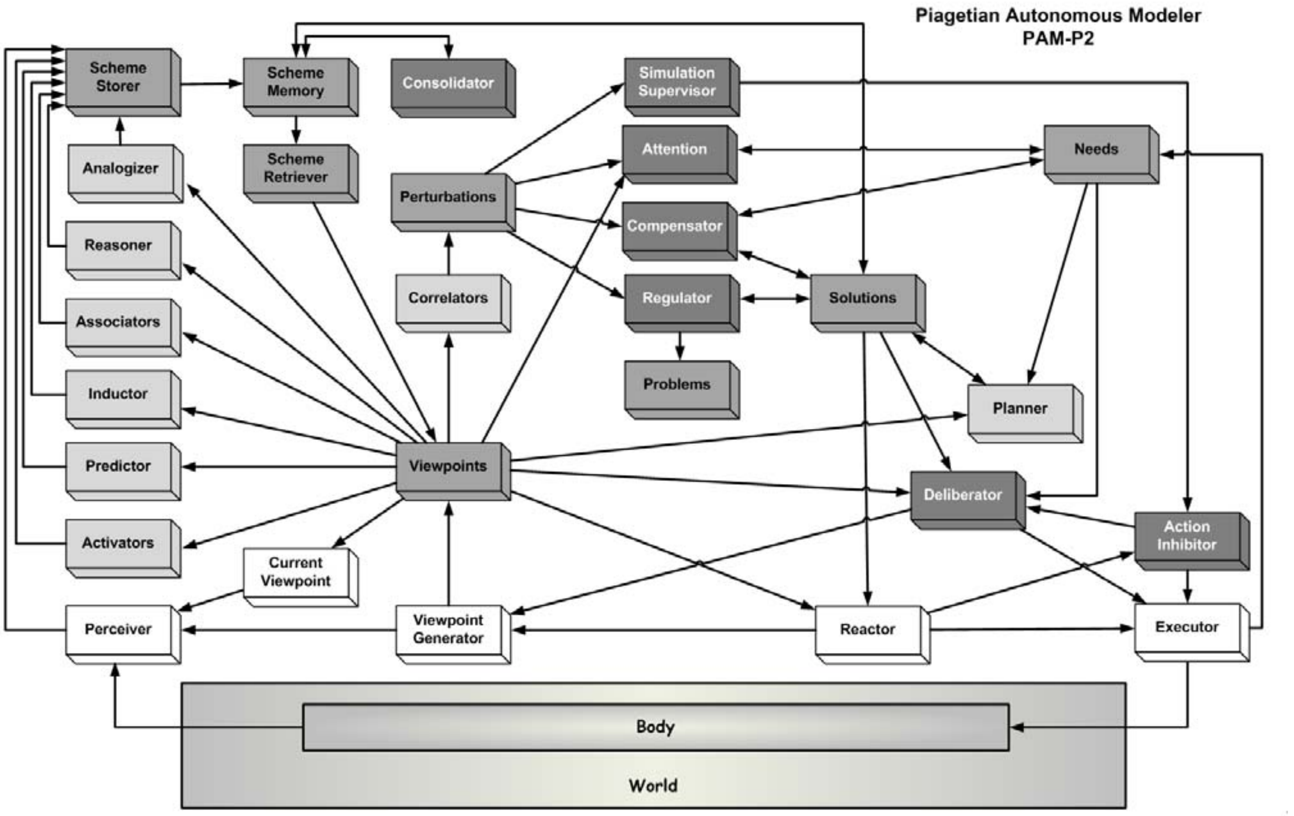


Figure 12. PAM-P2

The Temporal On, Off, and Void

A monad is considered On if it was activated after the Activation Threshold. Each monad has an *EnabledAt* property which identifies when the monad was last activated.

$$On := EnabledAt > ActivationThreshold \qquad (2)$$

A monad is considered Off if it was inhibited after the activation threshold. Each monad has an *ImpededAt* property which identifies when the monad was last inhibited. We can define the Off state as follows:

$$Off := ImpededAt > ActivationThreshold \qquad (3)$$

A monad is considered Void if it was not activated or inhibited after the Activation Threshold, or if it was simultaneously activated and inhibited, thereby rendering it neutral. We can define the Void state as follows:

$$\begin{aligned} Void :=&((ImpededAt < ActivationThreshold)\ and \qquad (4)\\ &(EnabledAt < ActivationThreshold))\ or\\ &(EnabledAt = ImpededAt) \end{aligned}$$

The activation of a monad is therefore determined by considering when the monad was last enabled or impeded with respect to the activation threshold.

```
Activation :=                                        (5)
  If (EnabledAt = ImpededAt)
  then 'Void'
  Elseif (EnabledAt > ActivationThreshold )
  then 'On'
  Elseif (ImpededAt > ActivationThreshold)
  then 'Off'
  Else 'Void'
```

Discussion

The idea of a neural proposition is not new, McCulloch and Pitts (1943) originally characterized neural activity as a mathematical proposition. Whereas McCulloch and Pitts emphasized neural activity as the basis of the proposition, the monemes and dynemes introduced here derive their structure from declarative propositions (e.g., UNISON, OPTION, etc.), and activation arises from an explicit merge type definition associated with each relation.

There are many knowledge representations in Artificial Intelligence—objects, propositions, frames, constraints, rules, and graphs abound. Why add another? None of the aforementioned knowledge representations effectively addressed Piaget's notions of monad and scheme or his expressed requirements for integration and differentiation.

Conclusions and Future Work

Using the preceding framework, neural propositions are used to construct a model of the PAM-P2 system's external world. Percepts, urges, and effects are asserted to the current internal model of the world (scheme memory). Inferential processes elaborate the model with newly synthesized monemes and dynemes.

The PAM-P2 prototype system is currently under development, and will have several experimental domains in which to test the models it autonomously generates.

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