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A Multi-Agent System Model to Advance Artificial General Intelligence based on Piaget's Theory of Cognitive Development

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Abstract. It is proposed a Multi-Agent System based on Piaget's theory of cognitive development aimed at progressing towards Artificial General Intelligence. Basic elements of Piaget's theory are presented. Also, the notion of will to power is extended to elucidate what tasks must be given to both, the Psychological and Epistemic subjects. By doing so it is modelled a functional organization in which positive reinforcement cycles help acquiring and organizing knowledge. These cycles are coined by us as volition towards intelligence. Next, an object-oriented model and an agent-based system are designed according to the theoretical background presented. Finally, a mathematical analysis on topology is provided to explain the apparent conundrum between the universal cognitive structures and the individual differences in cognition. Conclusions and future research are outlined.

Keywords. Cognitive development, narrow artificial intelligence, general artificial intelligence, topological structures, volition to intelligence.

1 Introduction

Human general intelligence (HGI) is the product of a transformational psyche, making humans general purpose problem solvers.

This cognitive flexibility is necessary in order to operate in many hierarchically structured frameworks across time. HGI can be regarded as the ability to perceive and represent any environment so it is possible to operate properly and effectively [13]. Inspired by HGI, the Artificial General Intelligence (AGI) hypothesis is presented as the creation of synthetic intelligences with broad scope and generalization capabilities [4].

AGI is a computing system that implements fully human intellectual ability and is equal in cognitive abilities to humans [22]. As pointed out by [23] AGI is the branch of computer science that studies intelligence by synthesizing intelligence. Artificial intelligence must take into account the fact that human intelligence is embedded in a world and is also embodied in an organic subject [11].

The author gives arguments to incorporate emotions, motivations, self-awareness, concepts that will help shape a strong intelligence, which could be an alternate label to AGI.

The assessment and ethical treatment of AGI systems that could be conscious and have subjective emotional experiences is done through a protocol presented in [9]. In [26] a brain-like computer architecture is favoured.

However, a physical computer is not currently able to incorporate all the complexity of a human brain. In [22] the architectural approach, widely employed to model information systems of organizations, is the basis to model an AGI system.

Table 1. The four stages of cognitive development proposed by Piaget

Stage	Age (Years)	Cognitive Structures
Sensorimotor	$t_1 \in [0,\ 2]$	Causality
		Time
		Space
		Object
Preoperational	$t_2 \in [2,\ 6]$	**Symbolic function:**
		Games
		Language
		Imitation
		Mental images
Concrete Operations	$t_3 \in [6,\ 12]$	**Set logic:**
		Grouping
		Classification
		Seriation
		Classes/Subclasses
		Reversibility
		Comparison
Formal (abstract) operations	$t_4 \in [12,\ 18]$	**Abstract logic:**
		Propositional logic
		Mathematical logic
		Deductive reasoning
		Meta-classification
		Combinatorial logic

The author also claims that artificial intelligence is still far from the human mind.

Thus, Artificial intelligence should be more cognitive-oriented, capable of generalizing representations, and incorporating cognitive concepts such as attention (i.e. in artificial vision systems and natural language processing), episodic memory and meta-learning.

Even though researchers propose developing human-level intelligence as a path to evolve artificial intelligence, the question of whether artificial intelligence can be psychologically achievable is still open [24]. Nonetheless, the literature on AGI indicates that intelligence is embedded in a world, i.e. the sensing of the world is a precursor to intelligence, and that any AI must also incorporate a socio-emotional plane.

Such precepts are pivotal in Piaget's theory of cognitive development [17, 19, 18, 16, 20]. Piaget not only emphasizes the cognitive tasks at each stage of development, but also demonstrates that social interactions are critical to the development of intelligence. Social interactions shape thinking, problem solving skills and help understanding social norms.

Social experiences contribute to social cognition, empathy and the ability to act properly in diverse situations. Incorporating Piaget's emotional plane in AGI systems is important to understand social cues so their behavior can be modified accordingly.

Figure 4 represents the cognitive and emotional planes in the development of HGI. It is explained in [1] that Piaget conceived an Epistemic Subject (ES) whose cognitive structures provide (i) an abstraction of Homo Sapiens self-constructed epistemology, and (ii) the spaces where knowledge is arranged.

Piaget's model explains how the ES develops general intelligence that provides the power to reason about domain-specific knowledge. Barbel Inhelder conceived a Psychological subject (PS) entity that explains the variations that the ES precludes, while simultaneously gives the mind a place to exist [7, 8, 1]. The ES applies universal rules to construct cognitive structures, while the PS decides its own goals and strategies. However, the interaction between them has not been modelled before.

In this paper we contribute to explain the foundations of intelligence with an axiom called volition to intelligence, which emerges after elaborating a hermeneutic analysis of Friedrich Nietzsche's will to power (Beyond good and evil (BGE) [12]).

The definition of power is that of Thomas Hobbes' [6]. Such philosophical foundations also allow us to design a novel Multi-Agent System (MAS) that implements the functional interplay between Psychological Subject Agent (PSA) and Epistemic Subject Agent (ESA).

Feldman's revised Piaget model [3] is also a major source of inspiration for developing the proposed AGI computational framework.

Finally, a mathematical analysis is outlined to explain how a universal cognitive structure is compatible with individual differences in cognition.

2 Piaget's Model of Cognitive Development

Piaget's theory rests on the notion of stages. A stage is conceived as a set of axiomatic pre-suppositions valid until such system fails because it is not sufficiently comprehensive, point at which a new stage is required [14].

Every new stage can do everything that the previous stage can plus account for all the things that the previous stage can not. As a consequence, knowledge is accumulated and has the potential to solve a wider set of problems.

The most powerful stage, called formal (abstract) operations, is reached when the ES is able to reason by using abstractions (language, mathematics, deductions and meta-classifications) and their associated rules. In this final stage, the reasoning is neither egocentric nor delusional.

Piaget's model of cognitive development is outlined in Tables 1 and 2, while a graphical description is given in Figure 4.

It helps understanding processes that, altogether, allows individuals to develop faculties of the mind that are flexible, supple, systematic, capable of organizing into more complex systems, and applicable to a variety of situations and experiences (Feldman dixit).

2.1 Feldman's Revised Model

In [3] it is proposed by Feldman a revision of Piaget's model for cognitive development. Feldman maintains the four original stages, as well as their time frame, except for the formal operations stage, which is extended into adulthood.

A major modification resides in the inclusion of two meta-processes called active construction and active extension and elaboration. These meta-processes are recurrent, i.e. they occur in each of the four stages of development, yet theirs actions are not the same.

Table 2. The four stages of emotional development proposed by Piaget

Stage	Affective Development
Sensorimotor	Instinctive impulses
	Objetivation of feelings
	Success vs Failure
	Pleasure vs Pain
Preoperational	Morality of obedience
	Regulation of interests
	Regulation of values
	Inter-individual
	Feelings
Concrete operations	Morality of cooperation
	Mutual respect
	Common rules
Formal (abstract) operations	Personality
	Messianic visions
	Grandiose plans
	Grandiose projects
	Self-centered theories

2.2 Piaget and Narrow Artificial Intelligence

The correspondence between human cognitive tasks of Piaget's model with the current advancement in Artificial Intelligence is depicted in Table 3. Nonetheless, unlike human intelligence, artificial intelligence does not have all that power integrated as a well-articulated computational framework, hence the current term narrow intelligence.

3 From the Will to Power to the Development of Intelligence

In this section, we justify a necessary axiom to explain the development of intelligence, which we call volition towards intelligence.

3.1 The Delight of Both, Volition and Accomplishment

Firstly, the link that unites life, volition and power is stated by Friedrich Nietzsche's will to power in BGE, section first, chapter 13.

Table 3. Correspondence between cognitive development and artificial intelligence

Stage	Cognitive structures	Artificial Intelligence
Sensorimotor	Causality	Classic robotics
	Time	Sensors
	Space	Data fusion
	Object	Object modelling and persistence
Preoperational	**Symbolic function:**	Semantic networks
	Imitation	Voice recognition
	Games	Voice-to-text mapping
	Language	Natural language processing
	Mental image	Information schemas
Concrete operation	**Set logic:**	Rule-based systems
	Grouping	Fuzzy logic types I and II
	Classification	Sorting algorithms
	Seriation	Unsupervised learning
	Classes and subclasses	Supervised learning
	Reversibility	Deep learning
	Comparison	
Formal (abstract) operations	**Abstract logic:**	Neuro-symbolic language processing
	Propositional logic	Prolog
	Mathematical logic	First-order predicate logic
	Deductive reasoning	Evolutionary programming
	Meta-classification	Bio-inspired algorithms
	Combinatorial logic	

Then, will or volition is explained in section first, chapter 19, where positive reinforcement cycles between a ruling entity and an operative entity are explained.

Volition is, therefore, a consequence of overcoming unfavorable conditions. This is clear in BGE section second, chapter 44. Finally, in section second, chapter 259, the conclusion regarding man's will to power is:

“The will to power will want to grow, extend, attract, be preponderant because it lives and because life itself is will to power. Thus, will to power is the ultimate will of life”.

A definition of power is taken from the Leviathan [6]:

“The power of a man, (to take it universally,) is his present means, to obtain some future apparent Good. And is either originall (sic), or instrumental. Natural power is the eminence of the Faculties of Body, or Mind: Strength, Forme (sic), Prudence, Arts, Eloquence, Liberality, Nobility”.

Therefore, the **volition towards intelligence** axiom is:

The type man possesses a strong and well-defined volition towards the eminence of the faculties of mind. Therefore, all the instances belonging to the class man possess a strong and well-defined volition, which moves the type man towards the development of higher and more comprehensive psychic states.

Table 4. Activities of the Psychological and Epistemic Subjects

Subject type	Attributions	Actions
Psychological	Commanding party	Uses subjects as instruments
		Detects when the environment is unknown
		Experiences a sensation of the condition away from which it goes
		Experiences a sensation of the condition towards which it goes
		Manifests a ruling thought
		Experiences the delight of command
		Aims at more comprehensive states
		Defines strategies according to its experiences
Epistemic	Operative party	Renders obedience
		Receives pressure
		Feels impulsion
		Confronts resistance
		Displays operative action
		Experiences delight of triumphing over obstacles
		Reaches a saturation point when the world is known territory
		Acts according to fixed laws of progression

3.2 The Delight of Ruling and Achieving

Charles Spearman stated that something is in charge of coordinating specific capabilities according to the context and the problem to solve.

This fits with Nietzsche's notion of a ruling party and an operative party, and also with the notion of a PS and ES.

Neuro-science has confirmed the existence of the dopaminergic incentive reward system located in the hypothalamus. This dopamine-mediated circuitry launches humans to explore, and then rewards when a goal is completed [14].

A goal-directed hierarchical organization promotes incentive reward at the same time that achieving progress validates the structure [13]. This suggests that emotions and motivation must be balanced and integrated. The interplay between the PS and the ES is given in Table 4.

4 The Multi-Agent System for AGI

4.1 The Object-Oriented Cognitive Structure

Piaget's theory along with Feldman's update are useful because they lead to an object-oriented structure in which the least powerful stage is at the top, while the most powerful is at the bottom (see Figure 2). The most powerful stage has the capacity to extend the routines that are defined in the immediate and upper stages; at the same time, it can also access routines in the upper stage that have the same name.

For example, the active construction phase in the formal operations stage extends what is done in active construction phase of the concrete operations stage.

However, when necessary, the formal operations stage can also order the execution of the active construction phase in the concrete operations stage.

The operations called active construction phase and active extension and elaboration phase are public, while the operation called beginnings of symbolic thought is private and only accessible by the sensorimotor stage through the routine called active extension and elaboration.

An object of the sensorimotor stage can take the form of any of the other stages. That is to say, one representative of the structure can be instantiated to take any role of the hierarchy with the faculty to execute any of the sub-routines available.

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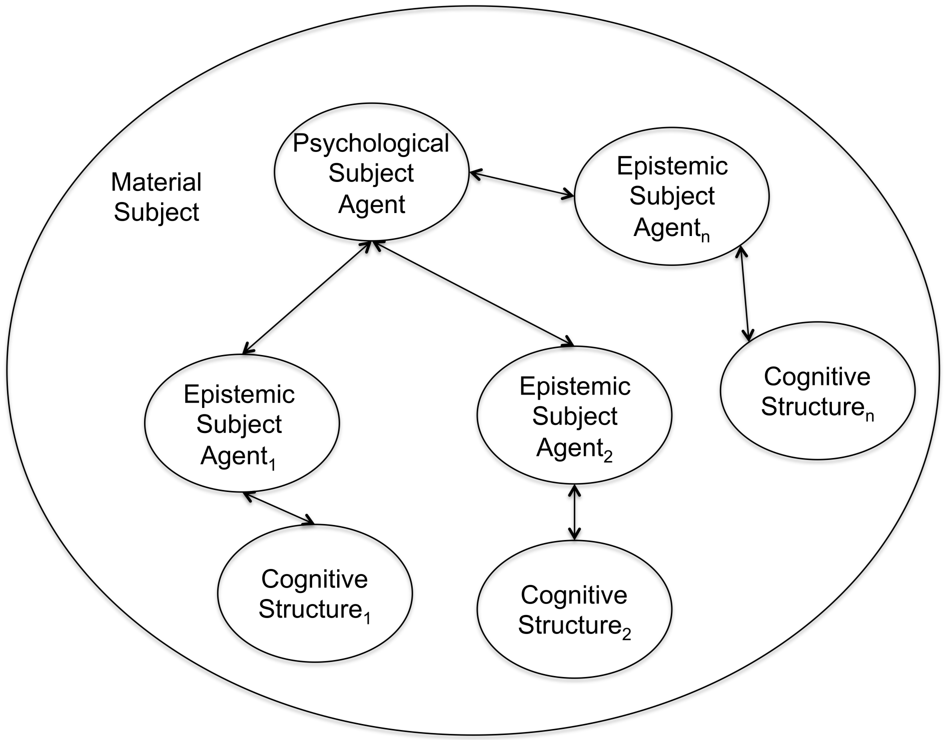

Fig. 1. Epistemic, psychological and material (either cybernetic or biological) agents

4.2 Psychological and Epistemic Agents

When studying HGI it is accepted that there is a psychological structure in charge of coordinating specific capabilities to solve a given problem in a given context. Within the Piagetian view the PS and the ES use strategies and procedures that relate functional and structural knowledge.

We deduce that Inhelder's Psychological Subject acts as the ruling party deciding what tools to use, while Piaget's Epistemic Subject is the operative faction.

Therefore, we propose an ensemble formed by Psychological Subject Agent (PSA) and Epistemic Subject Agent (ESA). The PSA launches as many ESA's as possible, while each ESA owns its cognitive structure represented in Figure 1.

Figure 3 is the activity diagram that models the interaction between the PSA and the ESA. The PSA assesses the environment, commands the execution of cognitive tasks and, by doing so, its role as commander is reinforced.

Then when the ESA completes the assigned task, it is praised by the PSA, action by which the PSA reinforces again its ruling role and the ESA reinforces its operative role. While the current cognitive structure is being formed, the PSA orders the execution of routines at such level.

On the other hand, when the ESA is no longer able to learn anything new, then the PSA orders the development of higher states, that is to say, to start forming a more elevated cognitive structure. Finally, after either decision, PSA explores the environment and the cycle repeats.

5 The "Structure as a Whole" and the "Individual Differences" Conundrum

As it is debated in [3], one of the major criticisms regarding Piaget's model of cognitive development is how to explain individual differences using the cognitive structures that are formed in each stage:

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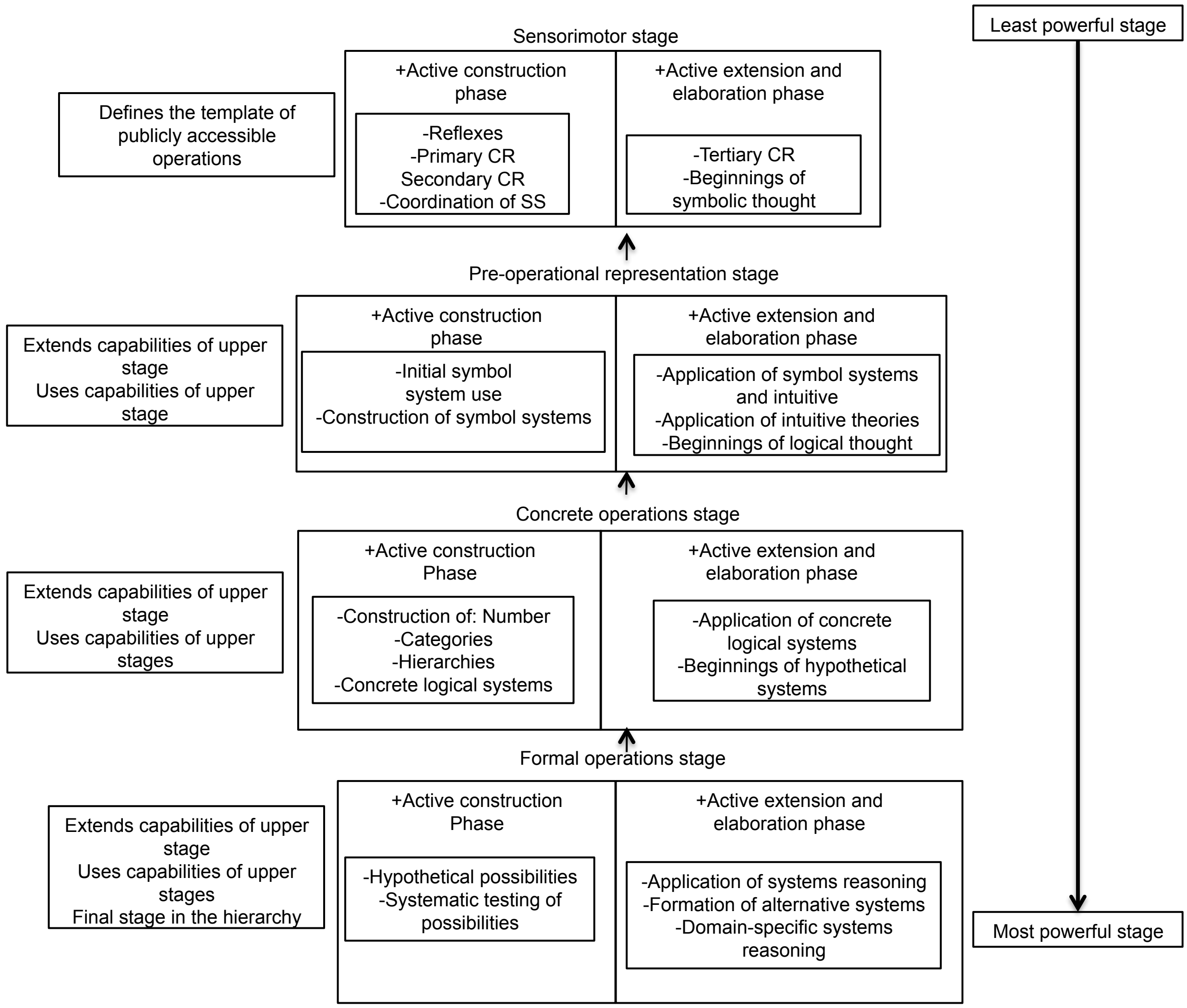

Fig. 2. The proposed object-oriented model of cognitive structures according to Feldman's insights

If the structures are universal, why people think differently? To solve this apparent conundrum let us recur to the mathematical branch called topology [21, 10].

Succinctly stated, topology studies the type of structures that keep elements of a set together, while preserving the properties of the structure under deformations.

A topology of a set defines the structure of a topological space. It can also be stated that a topological space is a set endowed with a structure.

The topology of a set X is called τ, and the topological space is a pair formed by $(X, \ \tau)$. However, for set τ to be a topology in X, it must fulfil specific criteria.

Suffices to say that the pair (X, τ) is a topological space in such a way that the sets contained in τ define the actual structure that keeps the elements in X together or "glued".

The model of cognitive development requires four elements to construct the cognitive structure in the sensorimotor stage (SMS). Thus:

$$\mathrm{SMS} = \{\text{Time}, \ \text{Object}, \ \text{Space}, \ \text{Causality}\}. \quad (1)$$

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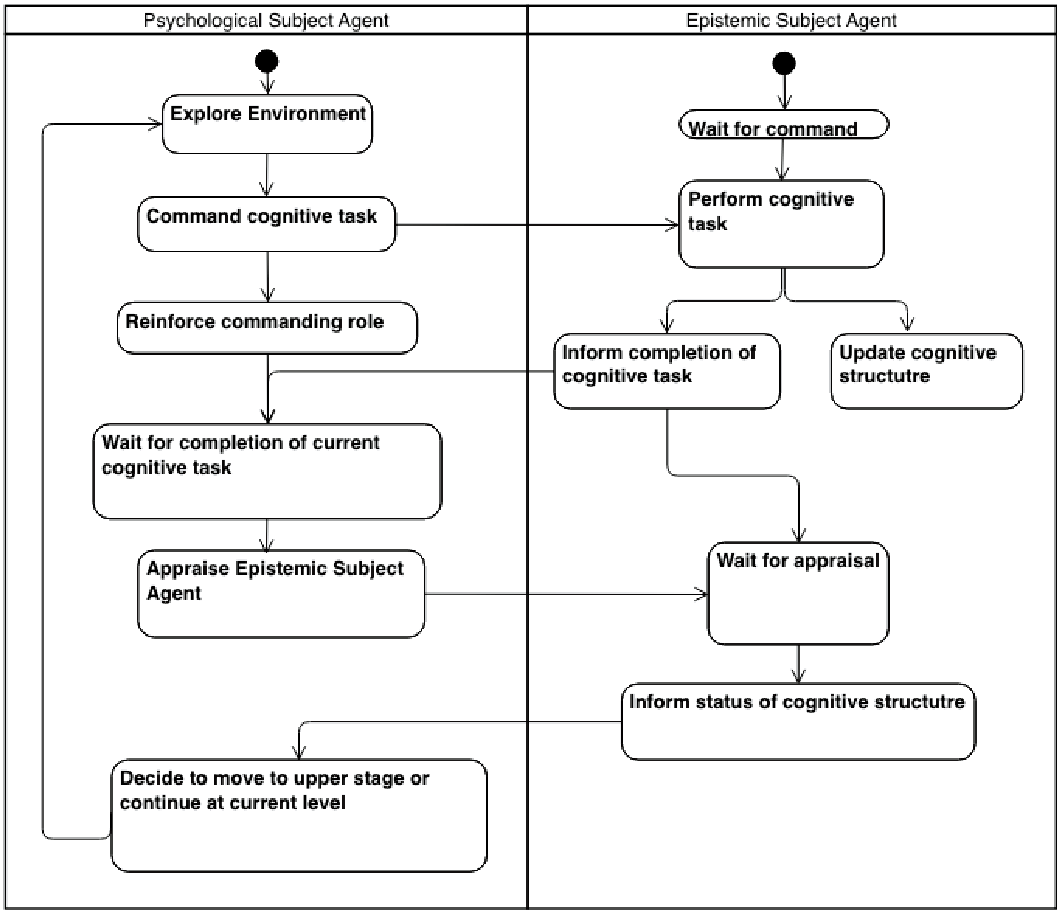

Fig. 3. Activity diagram of the ensemble PSA-ESA

Is the set containing the four concepts that define such stage. Therefore it can be envisioned a topology on set SMS defining the structure that maintains the elements of SMS together, and whose properties must be preserved under continuous mappings:

$$(\mathrm{SMS},\ \tau). \tag{2}$$

In this sense, a mapping from sensorimotor stage to pre-operational stage occurs such that the properties in SMS are preserved, otherwise learning does not occur.

However, according to [2], there are 355 different topologies τ for a set that consists of four elements, as it is the case in the sensorimotor stage.

Consequently, it can be stated that there is no universal cognitive structure, but 355 different structures that keep together Time, Object, Space and Causality. It gets even more complex, though.

By extending the theoretical framework for learning defined by [5], the elements in set SMS can be conceptualized as sets themselves:

$$\text{Time} = \{t_1,\ t_2,\ \cdots,\ t_t\}, \tag{3}$$
$$\text{Object} = \{o_1, o_2,\ \cdots,\ o_o\}, \tag{4}$$
$$\text{Space} = \{s_1, s_2,\ \cdots,\ s_s\}, \tag{5}$$
$$\text{Causality} = \{c_1, c_2,\ \cdots,\ c_c\}. \tag{6}$$

The actual structure, i.e. the topology, is formed by the values contained is each of Time, Object, Space, and Causality sets.

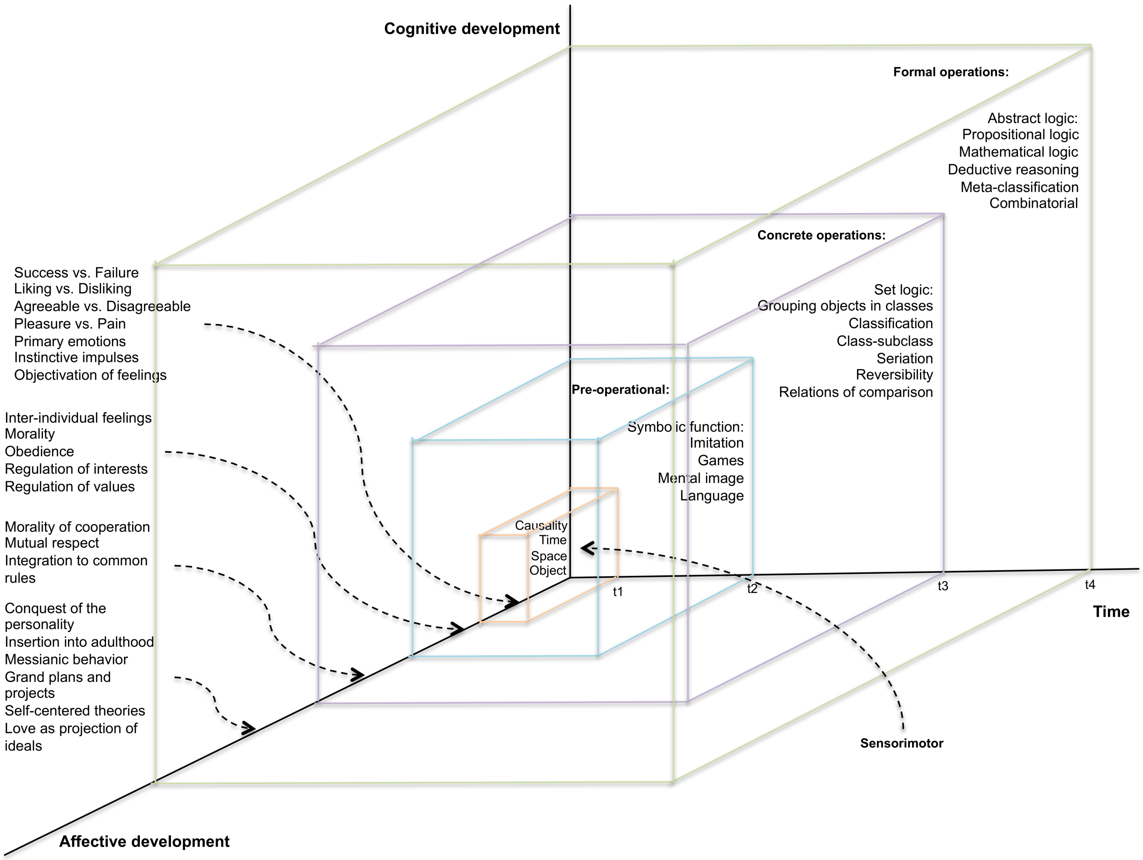

Fig. 4. Representation of Piaget's model as a three-dimensional space

Such contents depend on the perception and motor capabilities of each individual, given the fact that there are infinite facts to perceive. Thus, the number of topological spaces $(\mathrm{SMS},\ \tau)$ explodes.

Consequently, one factor that contributes to establishing different cognitive structures is the number of possible topological spaces, which for stage one is 355.

It can be stated that different individuals display different structures, even though the elements are the same. The context where individuals are located play a major role in how the structures are formed.

A study presented by [25] indicates that children in high socio-economic status present a higher starting point in infancy and greater gains in intelligence over time than for those children in low socio-economic status.

Moreover, as each individual perceives the world differently, the individual structures then ramify according to the actual values of the concepts Time, Object, Space and Causality that each individual possesses.

6 Conclusions and Future Work

Intelligence is an indicator of the effectiveness of abstract thoughts within an environment [15], premise on which Piaget's theory of cognitive development is sustained.

We evolve the proposition of will to power into an axiom called volition towards intelligence as the human drive to achieve even greater states of the faculty of the mind.

We associate the cognitive tasks in each stage of cognitive development with the set of current algorithms that comprise artificial narrow intelligence.

Even though it is not an exhaustive elaboration, it is enough to establish the correspondence between them. Two computational models are proposed, i.e. an object-oriented model for the cognitive structure, and an agent-oriented model to account for the concepts of Psychological and Epistemic Subjects.

In this agent model, the Psychological Subject Agent is the ruling class, while the Epistemic Subject Agent is the owner of one or several cognitive structures.

Afterwards, a mathematical analysis is given to explain the apparent conundrum of having a well-defined and universal cognitive structure with the fact that individual differences in cognition do arise.

Since intelligence is not the application of a specific mental operation but a selective combination of cognitive tasks that display an adaptive behavior in the face of a new problem, one open question refers to elucidate how a machine can employ harmoniously a set of algorithms that exist in the field of A.I. Another open question is how to incorporate the socio-emotional plane in order to regulate the solutions given by A. I.

Another line of research is the completion of the topological platform in order to explain the transformations and to define the saturation point of a given stage.

This future work includes the definition of proper homeomorphisms and the existence of homotopic functions that map one topological space to another maintaining the original structure.

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