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A computational model for the endogenous arousal of thoughts through Z*-numbers

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ABSTRACT

Natural language provides a rich combinatorial mechanism for encoding meanings - a finite set of words can express an unbounded number of thoughts. Framed in 2015 to extend the purpose of Zadeh's Z-numbers, a Z*-number is a perceptual symbol of the meaning of a natural language expression and consequently mentalese – or internal speech. This article, through decomposition of the Z*-macro-parameters into its atomic constituents, presents a model for the endogenous arousal of thoughts during empathetic, bespoke comprehension of the real-world. Based on Minsky's Society of Mind, the framework is founded on the assimilation of multimodal experiences, a sense of 'unified self' and its derivatives (choice, interest, curiosity, etc.), objective and subjective components of knowledge, commonsense, and attention dynamics over a real-world scenario. The model attempts emulation of slow and fast thinking, instinctive reactions, learning, deliberation, reflection and self-conscious decisions. The design has been validated against human responses, and aims to contribute to the development of autonomous artificial systems for man-machine symbiosis.

1. Introduction

A cognitive 'social' system [21,29,45] is intuitive, contemplative, possesses commonsense and rational decision-making abilities, is curious and creative, endogenously strives for resilience to an ever-changing world, can find structure in massive amounts of noisy and ambiguous data, learns from peers and first-hand experiences, and, above all, possesses a sense of self and empathy. This article documents our endeavours towards the design of a computational model of thinking for such a social system.

'Thinking' encompasses analysis of an event from a number of causal dimensions, sifting through possible propositions and solution schemes, improvisation, and application of strategies to arrive at the appropriate interpretation. This involves recall, manipulation and organization of a vast repertoire of commonsense, real-world and domain knowledge, and intricate automated reasoning processes. 'Mentalese [37]' refers to the 'inner speech' of contemplation. In other words, 'thinking' is the 'incremental mental manipulation of symbols [38]' that represent "*…intricate spatiotemporal patterns. These patterns serve as keys to unlock a tome of …knowledge, bathing the brain in the sights, sounds, smells, and physicality of …meaning.*" - [31].

In the 'Society of Mind [28]' and 'Emotion Machine [29]', Minsky dissects thinking into a number of layers – beginning with innate responses to stimulus, followed by learned, deliberative and reflective contemplation, to end with self-reflection and self-conscious reactions. This philosophy conceptually augments other cognitive models [11] with the sense of self-

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awareness, and hence forms the basis of our framework. 'Society of Mind' based architectures [14,15,25] have so far been unimodal and are yet to implement all the different aspects [10,38] of self-conscious reasoning.

If a social cognitive system were to emulate all the layers of thinking and self-consciousness for real-world comprehension, it would require data structures that facilitate expression of the self, encase subjective and objective knowledge constructs, and support representation of multisensory real-world information. The Z*-number [4,6] serves as a logical tool towards this purpose.

Z*-numbers are 'perceptual symbols [7]' of meanings embedded in natural language expressions, and thus for 'mentalese [37]' . The parameters of the paradigm encapsulate the context, subject, predicate, objective and subjective [2] time, and degrees of belief and affects in the information conveyed by an expression. Interactions between Z*-numbers resemble progressions through thoughts during comprehension. The synthesis of the intended model of contemplation, accordingly begins with decomposition of the macro-parameters of the Z*-number paradigm into their atomic constituents, formalization of their interdependencies and assimilation into an approximate procedure for thinking. Introducing the notion of the self and its derivatives (affects, choice, etc.) into equations of real-world decision-making is our primary contribution.

Though in its early stages of design, the proposed framework has attempted explicit coverage of the layers [28] in an active mind and different categories of thinking [22]. It handles various degrees of sensory awareness [8] of multimodal stimuli (both external and internal to the system). Endogenous and volitional attention distribution across components in a scenario, 'curiosity and interest' -driven [16,33] exploration of regions of interest, consideration of the actor and the observer's perspective, and bespoke behaviour are crucial features of the model. Preliminary steps to handling novel stimulus and concepts have been included as well. The design has been validated against responses of human subjects trying to comprehend a scenario. The model targets contribution in the domain of autonomous man-machine symbiotic system design.

The article begins with a brief elucidation on the properties of the Z*-numbers (Section 2.1), followed by enumeration of the building blocks of the model, as inferred from observations on thoughts (Section 3.1), translation of these identified macro-parameters into formalized relations involving their micro-constituents (Section 3.2) and integration of these relations into an algorithm of thinking (Section 3.3). Formulations cover representations and relations between parameters of thoughts (Section 3.2.1), perception (Section 3.2.2) and attention distribution (Section 3.2.3) over a dynamic region of interest. Section 4 presents results of a theoretical run-through the algorithm and analysis of the model.

2. Theory

2.1. Z*-numbers

While a Z-number [1,34,35,46] is an abstraction of the belief in the information in a simple *statement*, a Z*-number [4,6] is a metarepresentation of the 'dynamic meaning' of a *sentence*. Z*-numbers extend the capability of Z-numbers by virtue of parameters encapsulating the context, dynamicity and affects embedded in natural language sentences. These sentences could be external inputs or 'mentalese [37]' .

For a natural language sentence ($\boldsymbol{S}$) on a subject ($\boldsymbol{X}$) and with a predicate ($\boldsymbol{A}$), the Z*-number of S is:

$$Z^*(\boldsymbol{S}) = \langle \boldsymbol{C},\ \boldsymbol{T},\ \boldsymbol{A},\ \boldsymbol{B},\ \boldsymbol{AG} \rangle \quad (1)$$

where, $\boldsymbol{C}$= context that aroused S,

- $\boldsymbol{T}$= objective (absolute clock-time) and subjective (present, retrospective, prospective reference point) time-frame,
- $\boldsymbol{B}$= belief in the information conveyed by $\boldsymbol{S}$ for $\langle \boldsymbol{C}, \boldsymbol{T} \rangle$ and
- $\boldsymbol{AG}$=combination of 'basic [12]' affects, identified by the affect-type, strength and valence, construing the emotion embedded in $\boldsymbol{S}$.

Typically, $\boldsymbol{B}$ and the elements of $\boldsymbol{AG}$ are expressed as adjectives or adverbs and quantified as fuzzy numbers; $\boldsymbol{T}$ is a pointer to the time-line of evoked multisensory memories; and $\langle \boldsymbol{C}, \boldsymbol{T} \rangle$ help group related Z*-numbers into Z*-information sets.

The 6-tuple $\langle \boldsymbol{X}, \boldsymbol{C}, \boldsymbol{T}, \boldsymbol{A}, \boldsymbol{B}, \boldsymbol{AG} \rangle$ defines a Z*-valuation. It acts like a generalized constraint on $\boldsymbol{X}$, where:

$$\text{Probability}(\boldsymbol{X} \text{ is } \boldsymbol{A}) \text{ is}\left(\boldsymbol{B} *^{\boldsymbol{C}} \boldsymbol{AG}\right),\ \text{given } \langle \boldsymbol{C}, \boldsymbol{T} \rangle \quad (2)$$

$*^{\boldsymbol{C}}$ is an operator that integrates the complementary roles of $\boldsymbol{B}$ and $\boldsymbol{AG}$ in decision-making and consequently leads to the arousal of 'feelings [10]' in the system. [Refer [4,6] for properties of the paradigm.]

An example:

For $\boldsymbol{S}$= My mother called me!

- $\boldsymbol{C}$= Internal and external situational cues around the event, e.g. {The general setting when the summon was made, nature of the summon,...}
- $\boldsymbol{T}$= {Retrospective – when did I receive the call, what I was doing then, was I expecting the call; Present – how did the call affect me; Prospective – what do I intend to do about the call}
- $\boldsymbol{X}$= My mother's action
- $\boldsymbol{A}$= Call me

B = Definitely
AG = {⟨happy, strong, positive⟩ ∨ ⟨surprise, strong, positive⟩ ∨ ⟨apprehension, strong, negative⟩ ∨....}

Thus, the Z*-number of ***S*** = Z*(***S***) = ⟨{The general atmosphere when the phone rang / feelings with respect to the nature of the summon}, {Retrospective – when did I receive the call, what I was doing then, was I expecting the call. Present – how did the call affect me. Prospective – what do I intend to do about the call}, Call me, Definitely, {⟨happy, strong, positive⟩∨ ⟨surprise, strong, positive⟩ ∨ ⟨apprehension, strong, negative⟩ ∨....}⟩

A 'perceptual symbol [7]' of an event (***E***) or an object (***O***), is an abstraction of the 'system-state [18]' arising from the arousal and perception of associative patterns of objective and subjective features of causal and contextual multisensory stimuli pertaining to ***E*** or ***O***. Long-term memories of experiences and concepts are 'consolidations [42]' of perceptual symbols. While selective attention leads to the extraction of particular modal representatives of an ***E*** or ***O***; integration of these unimodal perceptual symbols generates all-around sensorial, proprioceptive and introspective experiences thereof (e.g. a cat has a visual, auditory, olfactory and tactile appeal).

Given a natural language expression (***S***) on an ***E*** or ***O***, Z*(***S***) records the system state (via ⟨***B, AG***⟩) and the internal and external reasons for it (via ⟨***C, T***⟩), and a fraction of related memories. These macro-parameters arise from the incremental conjunction of a melange of real-time multisensory external or internal inputs, activated sensations and memories. Z*(***S***) is therefore a perceptual symbol of an ***E*** or ***O***, and collaborations between a number of such associated Z*-numbers would generate concepts and ideas for anticipated memories, counterfactuals, and related emotions. Z*-numbers can thus be envisaged as operands of machine-mind processes (introspection, creativity, etc.). The concerns at this juncture are emulation of the endogenous instantiation of the Z*-number parameters in a machine-mind and mechanisms of interactions thereof giving rise to thoughts and ideas.

The following section describes our attempts at defining elements responsible for the autonomous arousal of the Z*-number parameters and using these formulations in the design of a model of thinking. A primary assumption, at this stage, is that the machine-mind is capable of mapping its feelings to linguistic expressions.

3. Proposed model

This section presents factors – through formulae and pseudocode – underpinning arousal of the Z*-number parameters in a machine mind. We begin by analysing observations on the macrocosm and microcosm of perceptions to extract influential micro-factors, followed by propositions of near-formal definitions for these elements. These thereafter converge into a potential algorithm for thinking in a social cognitive system.

3.1. Observations and inferences on thoughts

Every observation or a series of so, presented here, is followed by our inferences.

Observation_1. "*… look at the … words: Bananas, Vomit. A lot happened to you during the last second or two. You experienced some unpleasant images and memories, your face twisted slightly in …disgust. And you may have pushed this book imperceptibly farther away. Your heart rate increased, the hair on your arms rose a little, and your sweat glands were activated. In short you responded to the disgusting word with an attenuated version of how you would react to the actual event. All this was completely automatic, beyond your control.... your mind automatically assumed a temporal sequence and a causal connection between the words 'banana' and 'vomit', forming a sketchy scenario in which bananas caused the sickness. As a result you are experiencing a temporary aversion to bananas… The state of your memory has changed in other ways: you are now unusually ready to recognize and respond to objects and concepts associated with "vomit", such as sick, stink, or nausea, and words associated with "bananas", such as yellow, and fruit, and… apples and berries.... Furthermore,… you probably never encountered it* (these words together) *before and you experienced mild surprise… The essential feature of this complex set of mental events is its coherence. Each element is connected, and each supports and strengthens the others. The word evokes memories, which evoke emotions,… expressions and other reactions… The facial expression and the avoidance motion intensify the feelings to which they are linked, and the feelings in turn reinforce compatible ideas. All this happens quickly, yielding… cognitive, emotional, and physical responses that is both diverse and integrated.*" - [22]

The excerpt describes a typical comprehension-scenario involving the arousal of a constellation of autogenous internal events, mental processes, emotions and feelings, in response to multimodal 'images [10]' of stimuli. We understand that,

Inference_1.

(a) Generation and stabilization of thoughts is iterative and incremental [17,30] – traversing through cognitive, emotional and physical domains [28,42], and so should it be for the intended Z*-number based model of contemplation.
(b) Thoughts arise and are processed, both serially and in parallel [17,40], leading to a network of coherent ideas and concepts.

Observation_2. "*…we no longer think of the mind as going through a sequence of conscious ideas, one at a time. In the current view of how associative memory works, a great deal happens at once. An idea that has been activated… activates many ideas,* *which in turn activate others. Furthermore, only a few of the activated ideas will register in consciousness: most of the work of associative thinking is silent, hidden from our conscious selves.*" - [22]

This remark, arising out of delving deeper into the nature of thought processes, reinforces statements in Inference_1 and differentiates between foreground (conscious) and background (seemingly subconscious) activities. Thus,

Inference_2. If every atomic thought were interpreted as a Z*-number and a set of related Z*-numbers as Z*-information, and the system were assumed to be capable of manipulating Z*-information-sets, there should be Z*-equivalents of mentalese [37] of varying degrees of consciousness [8,10,40] in the machine-mind working memory [5,6].

Observation_3. "*Whenever you are conscious, and… even when you are not, multiple computations are going on in your brain, which maintain and update current answers to some key questions: Is anything new going on? Is there a threat? Are things going well? Should my attention be redirected? Is more effort needed for this task?*" - [22]

Furthermore,

Observation_4. "*A capacity for surprise is an essential aspect of our mental life, and surprise itself is the most sensitive indication of how we understand our world and what we expect from it. There are two main varieties of surprise – some expectations are active and conscious (you know you are waiting for a particular event to happen). But there is a much larger category of events that you expect passively: you don't wait for them, but you are not surprised when they happen. These are events that are normal in a situation, though not sufficiently probable to be actively expected…*" - [22]

Observation_5. "*We go through our lives seeing countless objects that we do not pay attention to. Without attention, the image or the sound or the feel does not register in the mind and may not be stored even briefly in memory. Our minds have a limited ability to process information about multiple objects at any given time. Because of limited processing resources, multiple objects present at the same time in the visual field compete for neural representation… – the winner is determined by the strength of the stimulus (brighter than the rest), by its strong association (familiarity), by its novelty (extraordinary), or most interestingly, by the demand of the task. Selectively focussing attention on targets significantly enhances neuronal responses to them. Attention seems to work by biasing the brain circuit for the important stimuli. When you attend to a stimulus, the suppression that distracters otherwise cause is reduced.*

Information reaches the brain from the outside world, but in an ever-changing context of internal representations… subjective experiences and responses and… final perceptions even more powerful than the stimulus itself.... Experience coupled with attention leads to physical changes in the structure and future functioning of the nervous system. … moment by moment we choose and sculpt how our ever-changing minds will work, we choose who we will be the next moment in a very real sense, and these choices are left embossed in physical form on our material selves." - [40]

Besides vetoing Inference_1 and inference_2, Observation_3 through Observation_5 lead to the understanding that,

Inference_3.

(a) Attention ($\boldsymbol{A_t}$) at time ($\boldsymbol{t}$), is an endogenous resource and a function of the environment (or context [23]) and the system-state [24] at $\boldsymbol{t}$. It regulates the nature of inputs to the system and subsequent comprehension.

Deployment of $\boldsymbol{A_t}$ for a stimulus ($\boldsymbol{St}$) stands for allocation of the required fraction of $\boldsymbol{A_t}$ for processing $\boldsymbol{St}$. The perception of a multisensory object ($\boldsymbol{obj}$) [e.g. a cat] is an integration of the perceptions of the individual constituent sensory stimuli ($\boldsymbol{St}$) [e.g. olfactory, visual, auditory and tactile elements].

Endogenous attention deployment and modulation occurs at different levels [2,43] – inter-object and intra-object. While the former equates to the fraction ($\boldsymbol{A_{t\_obj}}$) of $\boldsymbol{A_t}$ allocated to $\boldsymbol{obj}$ as a function of the multimodal appeal of $\boldsymbol{obj}$, the latter defines the division of $\boldsymbol{A_{t\_obj}}$ per $\boldsymbol{St}$ constituting the perception of $\boldsymbol{obj}$.

Exogenous attention deployment is when an $\boldsymbol{obj}$ is assigned $\boldsymbol{A_{t\_obj}}$ on external demand or instruction.

(b) 'Active' attention straddles 'noetic' and 'autonoetic' consciousness; 'passive' attention maps to 'anoetic' consciousness [44].

With reference to the observations and corresponding inferences highlighted here, the following section presents a model of the activities in the physical and mental space of an intelligent system as it observes the dynamic real-world, tries to comprehend it and adjusts its responses accordingly. The model aims to capture both, the 'actor' and the 'observer' perspectives. Section 3.2.1 focuses on the enumeration and description of thought and behaviour influencers, Section 3.2.2 on formulations on degrees of perception, and Section 3.2.3 on equations of autogenous and volitional attention dynamics in a multisensory environment. Section 3.3 presents our designed algorithm for contemplation during multisensory real-world comprehension. [Refer Table 1 for a summary of all the different parameters defined in the following section]

Table 1
Glossary of parameters.

Term	Definition	Eq. no.
internal_state(*time*)	= *F*(internal_state(*time*-1), context(region_of_interest, *time*-1)) or, *F*(internal_state(*time*-1), context(scenario, *time*-1)) = ***system_state***$_{sc}$(*time-1*) [Where, internal_state(*time* = 0) = *F*(values of parameters (like *health, interests, urges, drives*) defining the innate system self); context(region_of_interest, *time* = 0) = Φ	(3), (11)
region_of_interest(*modal_limits, time*)	= set of objects within *modal_limits* at *time*	(4)
modal_limits	$= \cup_{i=1}^{n}$ field of i^{th} modality	(5)
object_r	= semantic network of (*active_object_attribute, current_value*) tuples defining *object* in region_of_interest(*modal_limits, time*) = *F*(behaviour (*object, time*, context(scenario(*modal_limits*, $time_{t_0}$, $time_{t_n}$), *time*-1), internal_state(*time* −1))	(6), (16)
active_object_attribute	= *object* feature instantiated in region_of_interest(*modal_limits, time*)	
current_value of an *active_object_attribute*	= *F*(*location, source, activity*) of multimodal stimuli constituting *active_object_attribute* of *object* ∈ region_of_interest(*modal_limits, time*) $= C(\cup_{i=1}^{p}(\cup_{j=1}^{q_i} current\_value\_comp_{ji}))$ [Where, $\lvert modality\_act_i \rvert = q_i$ atomic signal components; $\lvert active\_object\_attribute \rvert = p$ modal signals constituting *active_object_attribute* of *object_r* ∈ region_of_interest(*modal_limits*, $time_t$)]	(7), (36)
scenario(*modal_limits, time_start, time_end*)	$= C(\int_{time\_start}^{time\_end} \text{region\_of\_interest}(modal\_limits,\ t)\ dt)$	(8)
context(region_of_interest(*modal_limits*, $time_t$), *time*)	$= C\ (\cup_{i=1}^{N} object\_r_i)$ at *time* [Where, $object\_r_i \in$ region_of_interest(*modal_limits*, $time_t$)] = *F*(reg_perception at *time*)	(9), (51)
context (scenario(*modal_limits*, $time_{t0}$, $time_{tn}$), *time*)	$= C(\int_{time_{t_0}}^{time_{t_n}} \text{context}(\text{region\_of\_interest}(modal\_limits,\ t),\ time)\ dt)$ = *F*(sc_perception at *time*)	(10), (53)
object_r$_{sc}$	= trajectory of *object* in scenario(*modal_limits*, $time_{t_0}$, $time_{t_n}$) or perception time-frame [$time_{t0}$, $time_{tn}$] $= \int_{time_{t_0}}^{time_{t_n}} object\_r_t$ in region_of_interest $(modal\_limits,\ t)\ dt$	(12), (47)
system_state$_{sc}$(*time*)	= system state (summary of urges, drives, plans and other information that facilitate continued system operation) over scenario(*modal_limits*, $time_{t_0}$, $time_{t_n}$) or perception time-frame [$time_{t0}$, $time_{tn}$] $= \int_{time_{t_0}}^{time_{t_n}}$ internal_state(t) in context(region_of_interest(*modal_limits*, t), *time*) *dt*	(13), (48)
behaviour(*object, time*, context(scenario (*modal_limits*, $time_{t_0}$, $time_{t_n}$), *time*-1), internal_state(*time*-1))	= *I*(context(scenario(*modal_limits*, $time_{t_0}$, $time_{t_n}$), *time*-1) ∧ internal_state(*time*-1)) arousing sensorimotor reactions in *object* at *time* = *F*($object\_r_{sc}$, $system\_state_{sc}$, *F*(context (scenario(*modal_limits*, $time_{t_0}$, $time_{t_n}$), *time*-1) ∧ internal_state (*time*-1))) arousing sensorimotor reactions in *object* at *time* = *F*(obj_perception(*object, time*-1, internal_state(*time*-1), context(region_of_interest(*modal_limits*, $time_t$), *time*)))	(14), (15), (49)
knowledge(*object*)	= semantic network of (sets of (*object_attribute, values, weight, reasons, belief, affects*,...) constituting (*real_experiences, anticipations, ideas, counterfactuals, commonsense, domain_knowledge, metaphors*,...) on *object*, irrespective of context, in system memory	(17)
object	covers the entire spectrum of physical artefacts and abstract events	
real_experiences	= set of actual episodes and associated qualia concerning *object*	
domain_knowledge	= set of factual knowledge on *object*, and events and elements that often occur in association with and influence interpretation of *object*	
commonsense	= procedural real-world knowledge	
reasons	= logic in support of comprehension of a fact (e.g. (*object_attribute, values*) compatibility)	
weight of *object_attribute*	= *F*(objective and subjective relevance of *object_attribute* for a particular sense of *object* across related *real_experiences, commonsense, domain_knowledge*,...)	(18)
object_m	= semantic network of (sets of (*object_attribute, normal_range*, outlier_instances, *c_weight, reasons, belief, affects*,...) constituting (*real_experiences, anticipations, ideas, counterfactuals, commonsense, domain_knowledge, metaphors*,...) on *object* ∈ (context(scenario(*modal_limits*, $time_{t_0}$, $time_{t_n}$), *time*) ± *c_threshold*) in system memory $= \cup_{i=1}^{n}$(subset of $essential_i$ of some $object\_m$ of $object_i$ ∈ long-term memory)	(19), (25)
c_threshold	= constraint on the perimeter of *object_m* = *F*(*real_experiences, commonsense, domain_knowledge* on *object* ∈ context(scenario(*modal_limits*, $time_{t_0}$, $time_{t_n}$), *time*))	(20)

(*continued on next page*)

Table 1 (*continued*)

Term	Definition	Eq. no.
normal_range	= heavily reinforced range of *values* for *object_attribute* in context = *F*(*real_experiences, commonsense, domain_knowledge* for *object* ∈ (context(scenario(*modal_limits*, $time_{t_0}$, $time_{t_n}$), *time*) ± *c_threshold*))	(21)
outlier_instances	= values representing unusual experiences or metaphors	
c_values	= {*normal_range, outlier_instances*} = $C(\cup_{i=1}^{n}(\cup_{j=1}^{m_i} sign\_component_{ji}))$ into {*normal_range, outlier_instances*}	(22), (31)
c_weight	= degree of importance of *object_attribute* in definition of *object* ∈ context = *F*(objective and subjective relevance of *object_attribute*, in definition of *object*, across *real_experiences, commonsense, domain_knowledge* on *object* ∈ (context(scenario(*modal_limits*, $time_{t_0}$, $time_{t_n}$), *time*) ± *c_threshold*))	(23)
knowledge(context(scenario(*modal_limits*, $time_{t_0}$, $time_{t_n}$), *time*)	= *C*(*object_m* of all *objects* experienced or envisioned in (context(scenario(*modal_limits*, $time_{t_0}$, $time_{t_n}$), *time*) ± *c_threshold*)) in system memory	(24)
essential set of an *object*	= set of *object_attributes* that distinguish one *object* from another in context [(*essential* ⊆ *object_m*); [|*essential*| = *rel_threshold* = number of crucial *active_object_attributes* in region_of_interest(*modal_limits*, $time_t$) for an *object_m* to be mapped to *object_r*]	
degree of curiosity	= *F*(emotion strength aroused by *object_r* stimuli)	(26)
primary *object_attribute* of *object*	= $F((imp\_mod_1 . modality_1), (imp\_mod_2 . modality_2),..., (imp\_mod_n . modality_n))$	(27)
modality$_i$	= *F*(m_i atomic constituents comprising the modality signal)	(28)
sign_component$_{ji}$	= signature of *component$_j$* of *modality$_i$* of *object_attribute* of *object* = ($normal\_range_{ji}$, $m\_outlier\_instances_{ji}$, $m\_threshold_{ji}$, m_em_{ji})	(29)
m_em$_{ji}$	= instinctive emotions or qualia due to *component$_j$* in *modality$_i$*	
imp_mod$_i$	= importance of *modality$_i$*, in *object_attribute*, in terms of innate emotion components $= F(\sum_{j=1}^{m_i} m\_em_{ji})$	(30)
primary *active_object_attribute* of *object_r*	= $F((imp\_amod_1 . modality\_act_1), (imp\_amod_2 . modality\_act_2),..., (imp\_amod_p . modality\_amod_p))$	(32)
modality_act$_i$	= *F*(atomic constituents constituting the *i*th modal signal of an *active_object_attribute* in region_of_interest (*modal_limits*, $time_t$)) [|$modality\_act_i$| = q_i atomic signal components]	(33)
current_value_comp$_{ji}$	**=** (perceived objective strength, innate emotional impact) of *component$_j$* of *modality_act$_i$* in region_of_interest(*modal_limits*, $time_t$) **=** (ob_value_{ji}, em_value_{ji})	(34)
imp_amod$_i$	= importance of *modality_act$_i$*, in *active_object_attribute*, in terms of innate emotion components. $= F(\sum_{j=1}^{q_i} em\_value_{ji})$	(35)
aff_imp	= affectual impact of *active_object_attribute*, due to novel *current_value_comp$_{ji}$* and reinforced *sign_component$_{ji}$*, on *c_weight* of $object\_attribute = F(\sum_{i=1}^{p} C(imp\_amod_i,\ imp\_mod_i))$	(37)
degree of curiosity due to x_n novel attributes $\propto C(\sum_{i=1}^{x_n}(\sum_{j=1}^{p_i}(imp\_amod_{ji} . \sum_{k=1}^{q_{ji}} em\_value_{kji})))$		(38)
degree of curiosity due to x_u unusual attributes $\propto C(\sum_{i=1}^{x_u}(c\_weight_i,\ (\sum_{j=1}^{p_i}(C(imp\_mod_{ji},\ imp\_amod_{ji}) . \sum_{k=1}^{q_{ji}} em\_value_{kji}))))$		(39)
degree of curiosity aroused by novel and/or unusual attributes ∝ *C*(curiosity due to x_n, curiosity due to x_u)		(40)
obj_perception(*object, time*, internal_state(*time*), context(region_of_interest(*modal_limits*, $time_t$), *time*))	= perception of *object_r* behaviour at *time* (***object_r$_{time}$***) = *F*($object\_r_{time}$, *time*, anticipation($object\_r_{sc}$, active_knowledge(*object, time*, internal_state(*time*), context(region_of_interest(*modal_limits*, $time_t$), *time*))))	(41)
active_knowledge(*object, time*, internal_state(*time*), context(region_of_interest(*modal_limits*, $time_t$), *time*))	= semantic network of fraction of *object_m* active at *time* (***object_m$_{time}$***) and associated memories in the system working memory = *C*($object\_m_{time}$ ∪ latent_memories(*object*, internal_state(*time*), context(scenario(*modal_limits*, $time_{t_0}$, $time_t$), *time*)) ∪ current_experiences($object\_r_{sc}$, $system\_state_{sc}$, context(scenario(*modal_limits*, $time_{t_0}$, $time_t$), *time*)))	(42)
latent_memories = semantic network of peripheral memories activated in response to *object_r*, context and internal_state at *time*; **latent_memories**(*object*, internal_state(*time*), context(scenario(*modal_limits*, $time_{t_0}$, $time_t$), *time*))) ⊆ ((knowledge(*object*) - *object_m*) ∪ knowledge(context(scenario(*modal_limits*, $time_{t_0}$, $time_t$), *time*)) ∪ …)		(43)
current_experiences($object\_r_{sc}$, $system\_state_{sc}$,(context(scenario(*modal_limits*, $time_{t_0}$, $time_t$), *time*))	= semantic network of (sets of (active_*object_attribute, current_value, cu_weight, reasons, belief, affects*,…) constituting (*real_experiences, anticipations, ideas, counterfactuals, commonsense, domain_knowledge, metaphors*,…) on *object* ∈ (context(scenario(*modal_limits*, $time_{t_0}$, $time_t$), *time*) through perception time-frame [$time_{t0}$, $time_t$]	(44)
cu_weight	= *F*(*c_weight* in $object\_m_{time}$, subjective and objective (*current_value*) revelations arising from *object_r*)	(45)

(*continued on next page*)

Table 1 (*continued*)

Term	Definition	Eq. no.
anticipation(*object_r$_{sc}$*, active_knowledge(*object, time*, internal_state(*time*), context(region_of_interest(*modal_limits, time$_t$*), *time*)))	= set of (*object_r$_{ex}$, ex_belief, ex_threshold*) tuples defining expectations for *object_r$_{time}$* [(*object_r$_{exi}$, ex_belief$_i$, ex_threshold$_i$*) tuple => *ith* probable value (*object_r$_{exi}$*) for *object_r$_{time}$*, belief (*ex_belief$_i$*) in the expectation, and limits (*ex_threshold$_i$*) of acceptability of *object_r$_{time}$* as equivalent to *object_r$_{exi}$*, given context and internal_state]	(46)
reg_perception(region_of_interest(*modal_limits, time$_t$*), *time*, internal_state(*time*))	= system's perception of a region_of_interest at *time* $=C(\cup_{i=1}^{n}$ (obj_perception (*object$_i$, time*-1, internal_state(*time*-1), context(region_of_interest(*modal_limits, time$_t$*), *time*))))	(50)
sc_perception(scenario(*modal_limits, time$_{t_0}$, time$_t$*), *time*)	= system's perception of an entire scenario at $time=C(\int_{time_{t_0}}^{time_t}$ (reg_perception(region_of_interest(*modal_limits, t*), *time*, internal_state(*time*)) dt)	(52)
object_r$_{time_i}$	= *object_r* of the *ith object* (*object$_i$*) ∈ region_of_interest(*modal_limits, time*); [$\lvert object\_r_{time_i}\rvert = Attr_{time_i}$ (*active_object_attribute, current_value*) tuples; $\lvert$region_of_interest (*modal_limits, time*)$\rvert = N_{time}$]	
object_m$_{time_i}$	= section of *object_m*, corresponding to *object_r$_{time_i}$*, active in the working memory at *time; object_m$_{time_i}$* ⊆ *object_m*	
$\boldsymbol{A_{time}}$	= total deployable system-attention at *time*	
$\boldsymbol{A_{time}}(i)$	= attention deployed for processing *object_r$_{time_i}$*	
$\boldsymbol{A_{time_{ji}}}$	= attention deployed for *active_object_attribute$_{time_{ji}}$*	
$\boldsymbol{A_{time_{kji}}}$	= attention allocated for *modality_act$_{time_{kji}}$*	
$\boldsymbol{A_{time_{lkji}}}$	= attention granted to *component$_l$* of *modality_act$_{time_{kji}}$*	
active_attention, act_obj_attention(*object*), **passive_attention, pas_obj_attention**(*object*)	=> Data structures in the machine-mind working memory. At the inter-object level: active_attention, passive_attention depict dynamic lists of *objects*, processed within consciousness awareness by the system or otherwise, respectively, where, for both lists, at any given *time*, $A_{time}(i) \geq A_{time}(j),\ \forall\ i < j$. At the intra-object level: act_obj_attention(*object*), pas_obj_attention(*object*) depict dynamic lists of *active_object_attributes* processed for an *object* within conscious awareness by the system or otherwise, respectively, where, for both lists, at any given *time*, $A_{time_{ji}} \geq A_{time_{ki}},\ \forall\ j < k$	
attn_threshold(*time*)	= innate factor deciding limits of conscious perception at *time*	
attn_mod_threshold(*modality_act, time*)	= intrinsic property determining system-sensitivity to a particular modal signal (*modality_act*) exuding from an *object* at *time*	
system_threshold(*time*)	= maximum number of elements that the system can consciously handle (parallely and co-operatively) at *time*	
$\boldsymbol{A_0}$	$= \sum_{i=0}^{N_0} A_0(i)$	(54)
$\boldsymbol{A_{0_{lkji}}}$	$= (F\ (em\_value_{0_{lkji}})\ .\ ob\_value_{0_{lkji}})$	(55)
$\boldsymbol{A_{0_{kji}}}$	$= (F\ (imp\_amod_{0_{kji}})\ .\ \sum_{l=1}^{q_{kji}} A_{0_{lkji}})$	(56)
$\boldsymbol{A_{0_{ji}}}$	$= (F\ (cu\_weight_{0_{ji}})\ .\ \sum_{k=1}^{p_{ji}} A_{0_{kji}})$	(57)
$\boldsymbol{A_0(i)}$	$= \sum_{j=1}^{Attr_{0_i}} A_{0_{ji}}$	(58)
common	= (region_of_interest(*modal_limits, t$_n$*) ∩ region_of_interest(*modal_limits, t$_{n-1}$*)); $\lvert common\rvert = com_n$, where $1 \leq com_n \leq N_{n-1}$	
known	= set of *objects* ∈ *common* mapped to some *object_m* using 19; $\lvert known\rvert = knw_n$	
comparable	= set of *objects* ∈ *common* mapped to some *object_m* using 25; $\lvert comparable\rvert = comp_n$	
unknown	= set of *objects* ∈ *common* unmapped to an *object_m* till t_{n-1}, the system is yet curious and has decided to continue exploration at t_n; $\lvert unknown\rvert = uknw_n$	
new	= (region_of_interest(*modal_limits, t$_n$*) – region_of_interest(*modal_limits, t$_{n-1}$*)); $\lvert new\rvert = new_n$	
$\boldsymbol{N_n}$	$= com_n + new_n;\ com_n = knw_n + comp_n + uknw_n$	
left	= (region_of_interest(*modal_limits, t$_{n-1}$*) – region_of_interest(*modal_limits, t$_n$*)); $\lvert left\rvert = ex_n$	
distractions	= set of *objects* in region_of_interest at t_{n-1} that the system has marked as irrelevant or unimportant or unidentifiable or a 'disturbance' and has consciously chosen not to process at t_n; $\lvert distractions\rvert = dist_n$	
$\boldsymbol{A_n}$	$= \sum_{i=0}^{N_n} A_n(i)$	(59)
For *objects* ∈ *new* $\boldsymbol{A_{n_{lkji}}}$	$= (F(em\_value_{n_{lkji}})\ .\ ob\_value_{n_{lkji}})$	(60)
$\boldsymbol{A_{n_{kji}}}$	$= (F(imp\_amod_{n_{kji}})\ .\ \sum_{l=1}^{q_{kji}} A_{n_{lkji}})$	(61)

(*continued on next page*)

Table 1 (*continued*)

Term		Definition	Eq. no.
	$\boldsymbol{A_{n_{ji}}}$	$= (F(cu\_weight_{n_{ji}}) \,.\, \sum_{k=1}^{p_{ji}} A_{n_{kji}})$	(62)
	$\boldsymbol{A_n(i)}$	$= \sum_{j=1}^{Attr_{n_i}} A_{n_{ji}}$	(63)
	$\boldsymbol{A_{n_{new}}}$	= total attention deployed for *new* at t_n [i => $object\_r_{n_i}$ ϵ *new*] $= \sum_{i=1}^{new_n} A_n(i)$	(64)
For *objects* ϵ *common*	$\boldsymbol{D_{imp_n}(i)}$	= degree of importance, interest and understanding of $object\_r_{n_i}$ in context(scenario, t_n) =*F*(obj_perception(*object*, $t_{(n-1)}$, internal_state($t_{(n-1)}$), context(region_of_interest, $t_{(n-1)}$)), *attn_threshold*(t_n), knowledge(*object*), knowledge(context), sc_perception(scenario(*modal_limits*, $time_{t_0}$, $time_t$), $t_{(n-1)}$), …)	(65)
	$\boldsymbol{D_{imp_{att\ jn}}(i)}$	= degree of importance of $active\_object\_attribute_{n_{ji}}$ in describing $object\_r_{n_i}$ in context(scenario, t_n) =*F*(knowledge(*object*), knowledge(context), sc_perception(scenario(*modal_limits*, $time_{t_0}$, $time_t$), $t_{(n-1)}$), $cu\_weight_{n_{ji}}$, novelty of $active\_object\_attribute_{n_{ji}}$, variance of $current\_value_{n_{ji}}$ from anticipation, *attn_mod_threshold* ($modality\_act_{n_{kji}}$, t_n) ∀ $modality\_act_{n_{kji}}$ ∊ $active\_object\_attribute_{n_{ji}}$, …)	(66)
	$\boldsymbol{A_{n_{kji}}}$	$= (C(imp\_amod_{n_{kji}},\ imp\_mod_{n_{kji}}) \,.\, \sum_{l=1}^{q_{kji}} A_{n_{lkji}})$	(67)
	$\boldsymbol{A_{n_{ji}}}$	$= (D_{imp_{att\ jn}}(i) \,.\, \sum_{k=1}^{p_{ji}} A_{n_{kji}})$	(68)
	$\boldsymbol{A_n(i)}$	$= (D_{imp_n}(i) \,.\, \sum_{j=1}^{Attr_{n_i}} A_{n_{ji}})$	(69)
	$\boldsymbol{A_{n_{common}}}$	= total attention deployed for *common* at t_n [i => $object\_r_{n_i}$ ϵ *common*] $= \sum_{i=1}^{com_n} A_n(i)$	(70)
$\boldsymbol{A_{(n-1)_{left}}}$		= total attention deployed for *left* at $t_{(n-1)}$ [i=> $object\_r_{(n-1)_i}$ ϵ *left*] $= \sum_{i=1}^{ex_n} A_{(n-1)}(i)$	(71)
$\boldsymbol{A_{(n-1)_{dist}}}$		= total attention deployed for *distractions* at $t_{(n-1)}$ [i => $object\_r_{(n-1)_i}$ ϵ *distractions*] $= \sum_{i=1}^{dist_n} A_{(n-1)}(i)$	(72)
$\boldsymbol{A_n}$		$= A_{n_{new}} + A_{n_{common}}$ [A_n is inclusive of ($A_{(n-1)_{dist}} + A_{(n-1)_{left}}$)]	(73), (74)

3.2. Formalization: model parameters

Notes:

i. The comma (,) in the formulations and open-endedness of some of the definitions, indicate our flexibility with the precision of how the factors integrate and leave scope for inclusion for other parameters in the future, respectively.
ii. *F, C* and *I* symbolize function_of, consolidation_of and interpretation_of operations, respectively.
iii. The 'integration' operator used across definitions is a symbolic representation of semantic information consolidation.
iv. The 'consolidation' operator implies complex interactions between "meanings" of memories activated, current_experiences, 'on the fly' realizations, reinforcements, identification of reasons for links between experiences, etc. This operator is particularly crucial in defining sub-contexts within the macrocosmic context of a scenario (as is evident in (9)).
v. The 'update' operator involves: reinforcement of relived experiences, appending new knowledge – experiences, realizations, clarifications etc., identification of errors, incorporating corrections with reasons, and consolidation of meanings and senses.

[*Refer Table 1 for a glossary of the parameters formulated in this Section.*]

3.2.1. Micro-parameters of thoughts and behaviour

"The world makes much less sense that you think. The coherence comes mostly from the way your mind works." - [22]

$$\begin{aligned}\textbf{internal\_state}(time) &= F(\text{internal\_state}(time-1),\ \text{context}(\text{region\_of\_interest}, time-1)) \\ &= F(health,\ curiosity,\ interests,\ choices,\ requirements,\ environmental\,cues,\\ &\quad memories,\ commonsense, \ldots)\ \text{at}\,time\end{aligned} \tag{3}$$

Where,

(a) internal_state(*time*) represents the system's 'experiencing self [22]' at *time*. It summarizes the minimum information that the system requires in order to continue functioning in the real-world.
(b) internal_state(*time*) influences [24] the *belief* and *affect* values for an event (***E***), which in turn modulates perception of ***E***.
(c) At $time = t_0$, when the system state is yet to identify and be influenced by the context,
   i. internal_state(t_0)=*F*(*health, interests, urges, drives,*… elements that define the innate system self at t_0) (Refer [10,38] for properties of the self).
   ii. context(region_of_interest, t_0)=Φ. [This is explained in (6).]

$$\textbf{region\_of\_interest}(modal\_limits, time_t) = \text{ set of } (objects \in modal\_limits) \text{ at } time_t \tag{4}$$

Where,

(a) region_of_interest represents a 3-dimensional snapshot or frame of a dynamic, multisensory, interactive physical or mental space bounded by *modal_limits* at $time_t$.
(b) The system ∈ region_of_interest(*modal_limits*, $time_t$).
(c) The system receives multimodal inputs from external *objects* as well as from within (imagination or mental representations of *objects*). Thus,

$$\begin{aligned}\boldsymbol{modal\_limits} &= \text{total area covered by available primary modalities of system}\\ &= \bigcup_{i=1}^{n} \text{field of } ith \text{ modality}\end{aligned} \tag{5}$$

In which, $n=$ number of available primary modalities, and *modal_limits* metaphorically equates to the concept of the Ego-sphere [36].
(d) A region_of_interest is a function of its constituent *objects* and their interactions. The system thus works towards comprehension of the region_of_interest and its derivatives through incremental accumulation of senses of its constituents. Ideally, $(comprehension_{\text{region\_of\_interest}(modal\_limits,\ time_t)} \leq comprehension_{\text{region\_of\_interest}(modal\_limits,\ time_{t+1})})$, [this point is further expressed in (50)] leading to,

$$\begin{aligned}\boldsymbol{object_r} &= \text{semantic network of properties of an } (object \in \text{region\_of\_interest}(modal\_limits, time_t))\\ &= \text{semantic network of } (active\_object\_attribute, current\_value) \text{ tuples defining an}\\ &\quad (object \in \text{region\_of\_interest}(modal\_limits, time_t))\end{aligned} \tag{6}$$

In which,

i. *object_r* equates to an instantaneous description of an *object* in region_of_interest(*modal_limits*, $time_t$).
ii. *active_object_attribute* is an *object* feature instantiated in region_of_interest(*modal_limits*, $time_t$). It could represent an innate property or arise out of solitary or interactions with other *objects* in region_of_interest(*modal_limits*, $time_t$).
iii. *current_value*=consolidated multisensory signals defining *active_object_attribute* in region_of_interest(*modal_limits*, $time_t$), or,

$$\begin{aligned}&\boldsymbol{current\_value} \text{ of } active\_object\_attribute = F(location, source, activity) \text{ of multimodal stimuli constituting}\\ &active\_object\_attribute \text{ of } (object \in \text{region\_of\_interest}(modal\_limits, time_t))\end{aligned} \tag{7}$$

[This point is elaborated in (36).]
iv. Sensory receptors of the system bind available stimuli exuding from a single or multiple *objects*. Each singular *object* defines a unit of a region_of_interest and the *object_r* is its real-time expression. An *object* could imply a real or an imaginary element, an atomic event, a single word or an expression.

A scenario is composed of a sequence of region_of_interest modules, i.e.,

$$\textbf{scenario}(modal\_limits, time\_start, time\_end) = C\left(\int_{time\_start}^{time\_end} \text{region\_of\_interest}(modal\_limits,\ t)\ dt\right) \tag{8}$$

where,

(a) A real-world scenario is composed of a sequence of frames of a dynamic, interactive environment. It captures a fraction of the behaviour and interactions between its constituent *objects*.
(b) $time\_start \leqslant time\_end$.
(c) |region_of_interest(*modal_limits*, t) ∩ region_of_interest(*modal_limits*, $t+\Delta t$)| ≥ 1
(d) Intuitively, scenario(*modal_limits*, t, t)=region_of_interest(*modal_limits*, t)
(e) Hypothetically, [*time_start*, (*time_start*+*dt*)] represents a fixation_point

An *object* in a scenario demonstrates context-sensitive behaviour. Thus, from (4) and (6),

$$\begin{aligned}&\textbf{context}(\text{region\_of\_interest}(modal\_limits, time_t), time)\\&= \text{semantics of region\_of\_interest}(modal\_limits, time_t) \text{ at } time\\&= C(\text{properties of all } (objects \in region\_of\_interest\ (modal\_limits, time_t)) \text{ at } time)\\&= C\left(\textstyle\bigcup_{i=1}^{N} object\_r_i\right) \text{ at } time\end{aligned} \tag{9}$$

Where,

(a) context(region_of_interest(*modal_limits, time*$_t$), *time*) summarizes semantics of region_of_interest(*modal_limits, time*$_t$) at *time*.
(b) |region_of_interest (*modal_limits, time*$_t$)| = N *objects*, $N \geq 1$.
(c) $object\_r_i = object\_r$ of the ith *object* in the region_of_interest.
(d) context influences the internal_state of the system, as is shown in (3). The context flavours comprehension and arouses emotions [10] in the system; internal_state is a culmination of the corresponding feelings [10] or qualia [3].
(e) The *time* parameter provides for differences in view-points or perspectives of a region_of_interest:
  i. $time_t < time$ ~ the system is deliberating on the past
  ii. $time_t = time$ ~ the system is processing the present
  iii. $time_t > time$ ~ the system is envisioning the future
(f) (9) conceptually extends to,

$$\begin{aligned}&\textbf{context}(\text{scenario}(modal\_limits, time_{t_0}, time_{t_n}), time)\\&= I(\text{scenario}(modal\_limits, time_{t_0}, time_{t_n})) \text{ at } time\\&= C(\text{features of } objects \text{ in scenario}(modal\_limits, time_{t_0}, time_{t_n})) \text{ at } time\\&= C\left(\int_{time_{t_0}}^{time_{t_n}} \text{context (region\_of\_interest } (modal\_limits, t), time)\, dt\right)\end{aligned} \tag{10}$$

Where, $time_{t_n}$ and *time* echo the relations stated in the preceding point, following which (3) translates into,

$$\textbf{internal\_state}(time) = F(\text{internal\_state}(time-1), \text{context}(\text{scenario}, time-1)) \tag{11}$$

Expanding (6) to plot properties of an *object* in a scenario, we arrive at,

$$\begin{aligned}&\boldsymbol{object\_r_{sc}} = \text{an } (object \in \text{scenario}(modal\_limits, time_{t_0}, time_{t_n}))\\&= \text{trajectory of } object \text{ through scenario}(modal\_limits, time_{t_0}, time_{t_n})\\&= \int_{time_{t_0}}^{time_{t_n}} (object\_r \in \text{region\_of\_interest}(modal\_limits, t))\ dt\end{aligned} \tag{12}$$

and, extending (3) to chart modulations in the system state through scenario, gives,

$$\begin{aligned}&\boldsymbol{system\_state_{sc}} = \text{system state over scenario}(modal\_limits, time_{t_0}, time_{t_n})\\&\int_{time_{t_0}}^{time_{t_n}} (\text{internal\_state } (t) \in \text{region\_of\_interest}(modal\_limits, t))\ dt\end{aligned} \tag{13}$$

(12) and (13) help map modulations in the internal_state for changes in *object_r* across scenario. A self-reflecting system would utilize these analyses to contemplate over counterfactuals, alternative actions, improvement strategies, etc.

In lieu of "Lewin's Grand Truism" [24], the behaviour of an *object* in a scenario can be simplistically defined as,

$$\begin{aligned}&\textbf{behaviour}(object, time, \text{context}(\text{scenario}(modal\_limits, time_{t_0}, time_{t_n}), time-1), \text{internal\_state}(time-1))\\&= F(I(\text{context}(\text{scenario}(modal\_limits, time_{t_0}, time_{t_n}), time-1) \wedge \text{internal\_state}(time-1)))\end{aligned} \tag{14}$$

Where,

(a) behaviour demonstrated by *object* at *time*, given scenario and internal_state, could be solitary or social, or intuitive or deliberated ('fast thinking or slow thinking' [22], respectively).
(b) Self-reflective behaviour would take into consideration results of (12) and (13), i.e.,

$$\begin{aligned}&\textbf{behaviour}(object, time, \text{context}(\text{scenario}(modal\_limits, time_{t_0}, time_{t_n}), time-1), \text{internal\_state}(time-1))\\&= F(object\_r_{sc}, system\_state_{sc}, I(\text{context}(\text{scenario}(modal\_limits, time_{t_0}, time_{t_n}), time-1) \wedge \text{internal\_state}(time-1)))\end{aligned} \tag{15}$$

(c) Intuitively, while (14) symbolizes near instantaneous behaviour at *time*, (15) would lead to self-conscious reflections over alternative view-points, counterfactuals, self-enrichment mechanisms, etc., towards improved handling of scenario($modal\_limits, time_{t_0}, time_{t_n}$) and similar.
(d) Equating (6), (12), (14) and (15): context summarizes the external environment, internal_state defines the system's choices, will, affects, etc.; and these collaborate to form reasons for system behaviour. Therefore,

$$\begin{aligned}&\boldsymbol{object\_r} \in \text{region\_of\_interest}(modal\_limits, time)\\&= F(\text{behaviour } (object, time, \text{context } (\text{scenario}(modal\_limits, time_{t_0}, time_{t_n}), time-1), \text{internal\_state}(time-1))\end{aligned} \tag{16}$$

In which,

(i) If,
- $time_{tn} = (time - 1)$, then *object_r* will be instantiated at *time*
- $time_{tn} > (time - 1)$, then *object_r* is being anticipated
- $time_{tn} < (time - 1)$, then *object_r* is being recalled

(ii) *object_r* simultaneously influences region_of_interest(*modal_limits, time*), context(region_of_interest(*modal_limits, time*) and internal_state(*time*).

The interpretation (I) and consolidation (C) operations in (8)–(10), (14) and (15), depend on the information generated through the following definitions:

"The masters of information have forgotten about poetry, where words may have a meaning quite different from what the lexicon says, where the metaphoric spark is always one jump ahead of the decoding function, where another, unforeseen reading is always possible" - J.M. Coetzee

Drawing from the above quote,

$$\begin{aligned}&\textbf{knowledge}(object) = \text{ semantic network of all } (real\_experiences, anticipations, ideas, counterfactuals,\\&commonsense, metaphors, domain\_knowledge, \ldots) \text{ on } object \text{ in system memory}\\&= \text{connected graph of (sets of } (object\_attribute, values, weight, reasons, belief, affects)) \text{constituting}\\&(real\_experiences, anticipations, ideas, counterfactuals, commonsense, metaphors, domain\_knowledge, \ldots)\\&\text{on } object, \text{ irrespective of context, in system memory}\end{aligned} \tag{17}$$

Where,

(a) knowledge(*object*) encapsulates all the different senses or 'meanings' – through multimodal representations of *real_experiences, imagination, metaphors*, etc. – of *object.*
(b) A semantic network or connected graph of associative knowledge is reminiscent of the Memex. Intuitively, knowledge(*object*) can be partitioned into different senses of *object*, where each sense is adaptively weighted in terms of rate of common-activation across contexts and subsequent reinforcement.
(c) knowledge(*object*) is dynamic as it is continually updated with new experiences and realizations.
(d) *object* covers the entire spectrum of physical artefacts and abstract events.
(e) *real_experiences* = set of actual episodes and associated qualia concerning *object.*
(f) *domain_knowledge* = set of factual knowledge on *object,* and events and elements that often occur in association with and influence interpretation of *object.*
(g) *commonsense* = procedural real-world knowledge leading to implicit behaviour.
(h) *object_attributes* depict properties that the system has learned to associate with *object.*
(i) *values* = set of rates (normal and outliers), arising out of experiences and commonsense; these apply to *object_attribute* across *object* senses; represent objective and subjective descriptors of *object_attribute* and could be precise numbers, numeric ranges, words or phrases. (See (22) and (31).)
(j) *weight* = the degree of importance of *object_attribute* for a specific sense of *object*,

$$\begin{aligned}\boldsymbol{weight} = F(&\text{objective and subjective relevance of } object\_attribute \text{ for a particular sense of } object \text{ across}\\&\text{related } real\_experiences, commonsense, domain\_knowledge, \ldots)\end{aligned} \tag{18}$$

In which, the objective relevance depends on the rate of reinforcement across time, and the subjective relevance is determined by strength and type of qualia aroused.

(k) *reasons* = logic supporting (*object_attribute, values*) and (*object, object_attribute, weight*) compatibility; is derived from contemplating over subnetworks of memories of *real_experiences, commonsense, domain_knowledge,* etc. underpinning concepts on *object* and *object_attribute.*
(l) *belief* = confidence in truth of (*object_attribute, values, reasons*). [Refer [4] for a study on the objective (e.g. reinforcement) and subjective factors (e.g. attachment-figures [28,29]) of *belief.*]
(m) *affects* = ensuing emotions and feelings.
(n) (Memory of *object* bounded by context(scenario(*modal_limits*, $time_{t0}$, $time_{tn}$), *time*)) ⊆ knowledge(*object*)), and,

$$\begin{aligned}&\boldsymbol{object\_m} = \text{memory of } (object \in \text{context (scenario}(modal\_limits, time_{t_0}, time_{t_n}), time))\\&= \text{semantic network of all } (real\_experiences, anticipations, ideas, counterfactuals, commonsense, metaphors,\\&domain\_knowledge, \ldots) \text{ on } (object \in (\text{context(scenario}(modal\_limits, time_{t_0}, time_{t_n}), time) \pm c\_threshold)) \text{ in}\\&\text{system memory}\\&= \text{connected graph of (sets of}(object\_attribute, normal\_range, outlier\_instances, c\_weight, reasons, belief,\\&affects, \ldots) \text{ constituting } (real\_experiences, anticipations, ideas, counterfactuals, commonsense, metaphors,\\&domain\_knowledge, \ldots) \text{ on } (object \in (\text{context(scenario}(modal\_limits, time_{t_0}, time_{t_n}), time) \pm c\_threshold))\\&\text{in system memory}\end{aligned} \tag{19}$$

In which,

i. Recollecting from (9) and (10), context equates to the 'interpretation' of a scenario; *object_m* therefore is a granule of knowledge(*object*) dealing specifically with *object* in contexts literally and metaphorically synonymous to the input.
ii. *c_threshold* = constraint on the perimeter of *object_m* = the minimum degree of required similarity between the input scenario and other elements in knowledge(*object*) to be considered as related. Intuitively,

$$\boldsymbol{c\_threshold} = F(real\_experiences,\ commonsense,\ domain\_knowledge \text{ on } (object \in \text{context}(\text{scenario}(modal\_limits,\ time_{t_0},\ time_{t_n}),\ time))) \tag{20}$$

iii. *object_attribute* is an *object* feature relevant to the input context.
iv. *normal_range* = heavily reinforced range of *values* for *object_attribute* in context, i.e.,

$$\boldsymbol{normal\_range} = F(real\_experiences,\ commonsense,\ domain\_knowledge \text{ for } (object \in (\text{context}(\text{scenario}(modal\_limits,\ time_{t_0},\ time_{t_n}),\ time) \pm c\_threshold))) \tag{21}$$

v. *outlier_instances* = *values* representing unusual experiences or metaphors. These instances carry higher subjective weight [22] compared to those associated with *normal_range*, due to the associated 'surprise'.
vi. {*normal_range, outlier_instances*} for *object_m* ⊆ *values* in knowledge(*object*), or,

$$\boldsymbol{c\_values} = \{normal\_range,\ outlier\_instances\} \tag{22}$$

vii. *c_weight* = the degree of importance of *object_attribute* in the definition of *object* in context, i.e.,

$$\boldsymbol{c\_weight} = F(\text{objective and subjective relevance of } object\_attribute, \text{ in definition of } object, \text{ across } real\_experiences,\ commonsense,\ domain\_knowledge \text{ on } (object \in (\text{context}(\text{scenario}(modal\_limits,\ time_{t_0},\ time_{t_n}),\ time) \pm c\_threshold))) \tag{23}$$

c_weight includes the impact of qualia associated with *c_values.*
viii. *reasons* = support for (*object_attribute, c_values*) and (*object, object_attribute*, context, *c_weight*) compatibility derived from analysis of sequences of relevant memories of *real_experiences, commonsense* and *domain_knowledge* on *object_attribute, object* and input context.
ix. *belief* = confidence in truth of (*object_attribute, c_values, c_threshold, c_weight, reasons*).
x. *affects* = ensuing emotions and feelings.

[Refer to Fig. 1 for a pictorial depiction of the relation between *object_m* and *object_r*]
Extending (17) and (19) to represent the system's knowledge on a context, we arrive at,

$$\begin{aligned}&\textbf{knowledge}\ (\text{context}\ (\text{scenario}(modal\_limits,\ time_{t_0},\ time_{t_n}),\ time)\\ &= (\text{semantic network of all } (real\_experiences,\ anticipations,\ ideas,\ counterfactuals,\ commonsense,\\ &domain\_knowledge,\ metaphors, \ldots) \text{ on all envisioned or experienced } (objects \text{ comprising}\\ &(\text{context}(\text{scenario}(modal\_limits,\ time_{t_0},\ time_{t_n}),\ time)\ \pm\ c\_threshold))\text{in system memory}\\ &= C(object\_m \text{ of all } objects \text{ experienced or envisioned in}(\text{context}(\text{scenario}(modal\_limits,\ time_{t_0},\ time_{t_n}),\ time)\\ &\quad \pm c\_threshold))\text{in system memory}\end{aligned} \tag{24}$$

Typically, knowledge(context) is dynamic – evolving with the system's exposure to the context and consequent comprehension. It can be partitioned into semantic sub-networks of episodes, weighted by reinforcement and strength of associated qualia [22]; *object_ms* constituting each such episode are weighted by their roles therein. Knowledge-stability necessitates percolation of modifications through related *object_ms* and corresponding knowledge(*object*)s, and vice-versa.

3.2.1.1. Relations between micro-parameters.

From (6) and (19): an *object_r* is an instantiated *object_m* within a region_of_interest(*modal_limits,* $time_t$), such that,

a) ($object\_r \cap object\_m$) = {$object\_attribute_1$, object_attribute$_2$, .., $object\_attribute_s$}
= set of 'active' *object_attributes* in region_of_interest(*modal_limits*, $time_t$)
b) If |*object_m*| = *N* attributes, then
{$1 \le |\, object\_m \cap object\_r| \le N$ = minimum requirement for (*object_r* = *object_m*), implying, *object_r* = *object.*
If *essential* = set of features or *object_attributes* particular to an *object* in a context, then
{$essential \subseteq object\_m$,
|*essential*| = *rel_threshold* = no. of crucial *active_object_attributes* in region_of_interest(*modal_limits*, $time_t$) for *object_r*, i.e., $essential \subseteq object\_r$,
$1 \le rel\_threshold \le |\, object\_m \cap object\_r| \le N$}}
c) ($object\_m \setminus object\_r$) = {$object\_attribute_1$, object_attribute$_2$, .., $object\_attribute_t$} = set of 'inactive' *object_attributes*
d) *object_r* is mapped to *object_m* iff ($essential \notin (object\_m \setminus object\_r)$)
e) ($object\_r \setminus object\_m$) = {($active\_object\_attribute_1$, $current\_value_1$), ($active\_object\_attribute_2$, $current\_value_2$), ...,
($active\_object\_attribute_p$, $current\_value_p$)} = set of novel *active_object_attributes*, given *object_m*, in region_of_interest(*modal_limits*, $time_t$),
i.e., $|object\_r \setminus object\_m| \ge 0$
f) Assuming the system possesses a concept of context(region_of_interest, *time*):
i. Let, $essential_i$ and $object\_m_i$ denote the *essential* set and *object_m* of the *ith object* ∈ knowledge(context) for context(region_of_interest, *time*), respectively
If ($\exists essential_i \in (object\_m_i \cap object\_r)$), then
{$object\_r \sim object\_m \sim object$,
If ($|object\_r \setminus object\_m_i| > 0$), then
{*object_r* includes at least one novel (*active_object_attribute, current_value*) tuple, given $object\_m_i$, implying *object_r* is possibly a 'novel' representation of $object\_m_i$,
updated $object\_m_i$ (and subsequently updated knowledge(*object*) and updated knowledge(context)) = *C*($object\_m_i \cup$ (*object_r* and associated experiences)),
|updated $object\_m_i$| = $|object\_m_i| + |object\_r \setminus object\_m_i|$}}
ii. If ($|object\_r \setminus object\_m| = |object\_r|$) ∀ *object_m* ∈ knowledge(context), then
{*object_r* is possibly 'novel' to the context,
If ($object\_r \ne$ (*object* ∈ long-term memory)), then
{*object_r* is possibly 'completely novel' to the system,
system creates a slot in long-term memory for a new *object*, such that,
{$object_{new}$ = a name that system semantically identifies *object_r* with (∼ fast mapping by infants [26]),
system incrementally prepares:
a) $object\_m_{new} = object\_m$ for $object_{new} = C(object\_r, object\_m)$ [where, *object_m* comes from (25)],
b) knowledge($object_{new}$) = $object\_m_{new}$,
c) updated knowledge(context) = *C*(knowledge(context) ∪ knowledge($object_{new}$))}}
Else
{$\exists object_x$: $object\_r = object_x$ based on $essential_{object\_x}$ in some $context_x \ne$ context(region_of_interest, *time*),
$object\_m_x$ = system instantiated *object_m* for $object_x$ ∈ context(region_of_interest, *time*) = *object_r*,
updated knowledge($object_x$) = *C*($object_x$, $object\_m_x$),
updated knowledge(context) = *C*(knowledge(context) ∪ $object\_m_x$)}}
g) Continual exposure to $object_{new}$ and reinforcement of its attributes, would lead to identification of $essential_{object_{new}}$.
h) If ($\exists object\_r \sim object_{new}$), where *object_r* contains information on the actual semantic name (*sem_name*), then
{updated knowledge($object_{new}$) = *C* (updated knowledge($object_{new}$) ∪ *sem_name*) [i.e., system learns *sem_name*]} (This is applicable for novel *active_object_attributes* as well).
i) If an *object_r* maps to a multitude of *objects* (analogous to being reminded of a number of *objects*), then
the consequent activated *object_m* is equivalent to:

$$\boldsymbol{object_m} = \bigcup_{i=1}^{n} (\text{subset of } essential_i \text{ of some } object_{m_i} \text{of } object_i \in \text{long term memory}) \tag{25}$$

Where,

i. *object_m* represents consolidated memories of *n objects* bearing various degrees of similarity with *object_r*
ii. (degree of similarity of *object_r* with $object_i$) ∝ ($|essential_i \cap object\_r|$)
iii. Intuitively, while novel *object_r*s will mostly be interpreted as per (25), *object_m*s of known *objects* will ideally be a combination of (19) and (25) where properties due to (19) dominate. This point reinstates the associativity of knowledge across domains.
iv. If an *object_r* is interpreted entirely in terms of (25), then system creates a slot for an $object_{new}$ in the long-term memory.
v. Novelty of *object_r*, intuitively induces curiosity and interest which influences the system's behaviour (exploratory or otherwise) towards it; where,

$$\textbf{degree of curiosity} = F(\text{strength of emotions aroused by } object\_r \text{ stimuli}) \tag{26}$$

(26) is an elementary representation of observations on the arousal of emotions and their translation into feelings in [10]. (27) through (40) elaborate on the concept of *object_r* stimuli mentioned in (26). Fig. 1 illustrates the relation between *object_r* and *object_m*.

From [8], and definitions (6), (7), (17) and (19), we arrive at the following micro-interpretations (from the observer's perspective) of components in a region_of_interest(*modal_limits*, $time_t$): [Refer Fig. 2 for a summary of the hierarchical relation amongst these elements.]

a) *object_attributes* can be differentiated into primary and composite ones, where the primary attributes derive from properties of modal signals exuding from *object*, and the composite ones are functions of primary and composite ones.

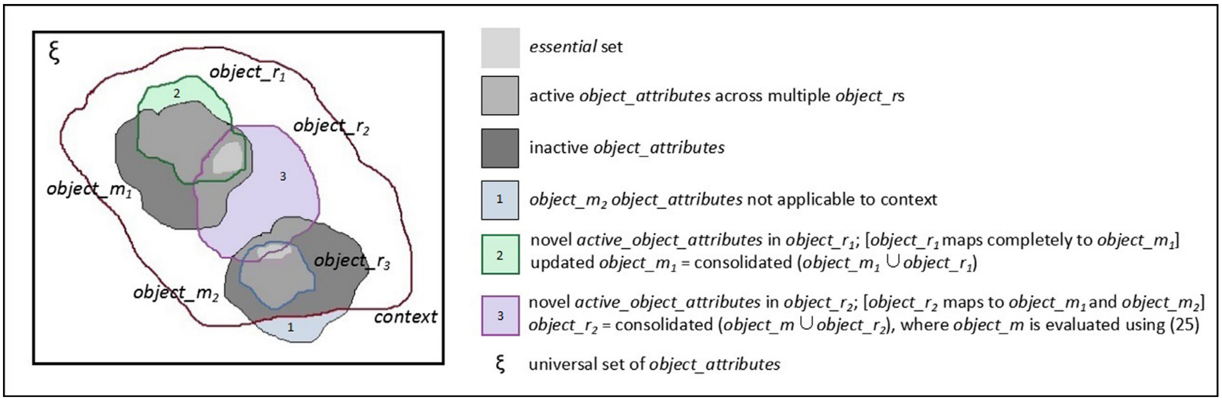


Fig. 1. Relation between *object_m* and *object_r*.

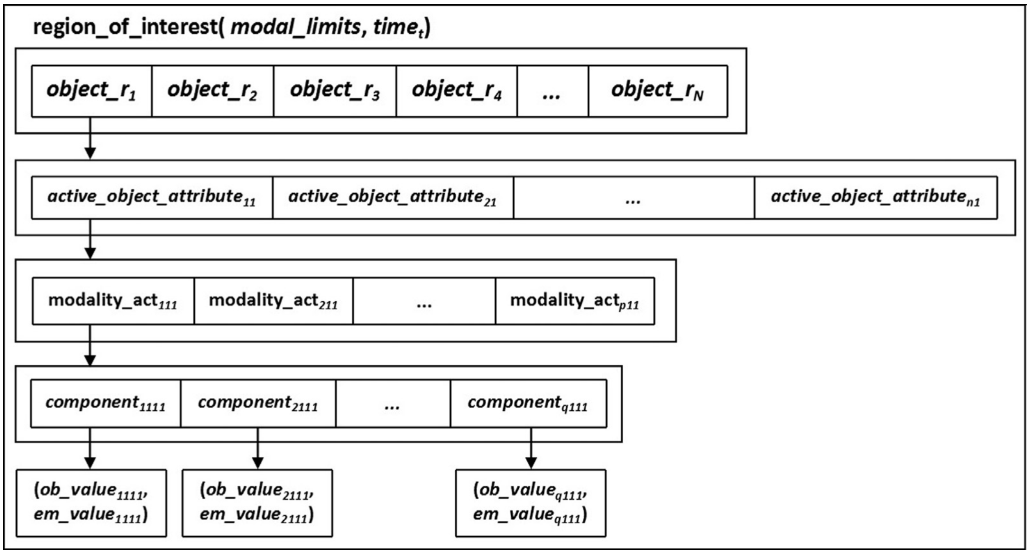


Fig. 2. Hierarchy of building blocks comprising a region of interest (*modal_limits, time$_t$*).

Thus, within the framework of a context,

$$\text{primary } \boldsymbol{object\_attribute} = F((imp\_mod_1 \,.\, modality_1),\ (imp\_mod_2 \,.\, modality_2), \ldots,\ (imp\_mod_n \,.\, modality_n)) \tag{27}$$

In which,

i. $|object\_attribute| = n =$ No. of modal signals composing *object_attribute* of *object.*
ii. $modality_i = i$th modal signal, where,
$|modality_i| = m_i$ = No. of atomic signal components (e.g., amplitude, frequency in an audio stimulus) constituting $modality_i$, i.e.

$$\boldsymbol{modality_i} = F(m_i \text{ atomic constituents}) \tag{28}$$

and,

$$\begin{aligned}\boldsymbol{sign\_component_{ji}} &= \text{signature of } component_j \text{ of } modality_i \text{ of } object\_attribute \text{ of } object \\ &= \left(normal\_range_{ji},\ m\_outlier\_instances_{ji},\ m\_threshold_{ji},\ m\_em_{ji}\right)\end{aligned} \tag{29}$$

In which,

- $normal\_range_{ji}$ = heavily reinforced value range for $component_j$,
- $m\_outlier\_instances_{ji}$ = exceptional experiences concerning $component_j$,
- $m\_threshold_{ji}$ = value limits defining acceptability of an instantiated $component_j$ of $modality_i$ as leading to *object_attribute* of *object*.

- $normal\_range_{ji}$, $m\_outlier\_instances_{ji}$, $m\_threshold_{ji}$ depict objective elements of $component_j$
- m_em_{ji} = instinctive emotions [10,29] or qualia [3] due to $component_j$, such that,

$$\boldsymbol{imp\_mod_i} = F\left(\sum_{j=1}^{m_i} m\_em_{ji}\right) \tag{30}$$

imp_mod_i summarizes the qualitative importance of $modality_i$, in *object_attribute*. The sum of all constituent imp_mod_i, contributes to the subjective weight (shown in (23) and (37)) of *object_attribute* in the description of *object*. (30) arises from studies [22,38] on the role of modal affects in recognition and recollection. Typically, *essential* comprises *object_attributes* with high objective weight or subjective weight, or both.

iii. The association of modal signals and their constituents to *object_attributes* and *object*, derive from the system's continued exposure to these elements, giving rise to *real_experiences, anticipations, commonsense*, associated *domain_knowledge*, etc.
iv. Equating (19), (22), (27), (28), (29) and (30),

$$\begin{aligned}&\boldsymbol{c\_values} \text{ for } (object\_attribute \in object\_m)\\ &= C\left(\bigcup_{i=1}^{n}\left(\bigcup_{j=1}^{m_i} sign\_component_{ji}\right)\right)\text{into } \{normal\_range,\ outlier\_instances\}\end{aligned} \tag{31}$$

(b) A system, observing or participating in a dynamic region_of_interest, is subjected to multisensory stimuli from *objects*. Thus, drawing from definitions above, Fig. 1 and Section 3.2.1.1,

$$\begin{aligned}&\text{primary } \boldsymbol{active\_object\_attribute}\\ &= F((imp\_amod_1 \,.\, modality\_act_1),\ (imp\_amod_2 \,.\, modality\_act_2), \ldots,\ (imp\_amod_p \,.\, modality\_act_p))\end{aligned} \tag{32}$$

In which,

i. $|active\_object\_attribute| = p =$ No. of modal signals constituting *active_object_attribute* of *object_r* in region_of_interest(*modal_limits*, $time_t$).
ii. $|modality\_act_i| = q_i$ = No. of atomic signal components of the i^{th} modal signal ($modality\_act_i$) constituting *active_object_attribute* i.e.,

$$\begin{aligned}&\boldsymbol{modality\_act_i} = F\big(q_i \text{ atomic constituents constituting the } i^{th} \text{ modal signal of an}\\ &(active\_object\_attribute \in \text{region\_of\_interest } (modal\_limits,\ time_t))\big)\end{aligned} \tag{33}$$

and,

$$\begin{aligned}&\boldsymbol{current\_value\_comp_{ji}} = \text{value of } component_j \text{ of } modality\_act_i \text{ in region\_of\_interest } (modal\_limits,\ time_t)\\ &= \left(ob\_value_{ji},\ em\_value_{ji}\right) = (\text{perceived objective strength, innate emotional impact}) \text{ of } component_j \text{ of}\\ &(modality\_act_i \in \text{region\_of\_interest } (modal\_limits,\ time_t))\end{aligned} \tag{34}$$

such that,

$$\boldsymbol{imp\_amod_i} = F\left(\sum_{j=1}^{q_i} em\_value_{ji}\right) \tag{35}$$

imp_amod_i describes the hardwired somatic marker [10] for $modality\_act_i$. It influences internal_state and accordingly attention [shown in (56), (61), (67)] and subjective weight of *active_object_attribute* [depicted in (37), (44), (57), (62)]
iii. Equating (7), (32), (33), (34) and (35),

$$\boldsymbol{current\_value} \text{ of } active\_object\_attribute = C\left(\bigcup_{i=1}^{p}\left(\bigcup_{j=1}^{q_i} current\_value\_comp_{ji}\right)\right) \tag{36}$$

current_value could be expressed as a precise number, an adjective, or an adverbial phrase.
iv. $current\_value\_comp_{ji}$ embeds [20] spatio-temporal cues of stimulus-components.
v. For context (region_of_interest, *time*),

If ((*essential* ∈ (*object_m* ∩ *object_r*)) ^ (*object_m* ∈ knowledge(context)))
{If (*active_object_attribute* ∈ *object_m*), then
{*active_object_attribute* = real time expression of *object_attribute*,
($modality\_act_i$ in *active_object_attribute*) = real time manifestation of ($modality_i$ in *object_attribute*) in region_of_interest(*modal_limits*, $time_t$),
$|modality\_act_i| = q_i = |modality_i| = m_i$ atomic components,
$|active\_object\_attribute| = p = |object\_attribute| = n$ modal signal constituents,
If (*current_value* ∈ *c_values*), then
(*active_object_attribute, current_value*) is reinforced in *object_m*

Else
{For all components of all modal signals constituting *active_object_attribute*
{If (for a $component_j$ of $modality\_act_i$ in *active_object_attribute*, ($ob\_value_{ji} \notin$ {$usual\_range_{ji} \pm m\_threshold_{ji}$, $m\_outliers_{ji}$}), then
{em_value_{ji} = 'surprise' proportional to the degree of variance of ob_value_{ji} from $sign\_component_{ji}$ and influences imp_amod_i,
$current\_value\_comp_{ji}$ => novel experience, thus
(a) updated $m\_outliers_{ji} = (m\_outliers_{ji} \cup ob\_value_{ji})$ [novel experiences are initially registered as $m\_outliers_{ji}$ and are promoted to $usual\_range_{ji}$ on sufficient reinforcement]
(b) $m\_threshold_{ji}$ is updated to accommodate changes in $usual\_range_{ji}$,
(c) updated $m\_em_{ji} = C(m\_em_{ji}, em\_value_{ji})$,
(d) updated $sign\_component_{ji} = (sign\_component_{ji} \cup$ updated $m\_outliers_{ji} \cup$ updated $m\_em_{ji})$,
(e) update *c_values* for *object_attribute* using updated $sign\_component_{ji}$ in (31)}
Else,
$current\_value\_comp_{ji}$ of $modality\_act_i$ reinforces $sign\_component_{ji}$ of $modality_i$}}
updated objective component of *c_weight* for *object_attribute* = *F*(reinforcement across all constituent $sign\_component_{ji}$)
updated subjective component of *c_weight* for *object_attribute* = *C* (subjective element in *c_weight, aff_imp*); where (from (23), (30), and (35)),

$$\boldsymbol{aff\_imp} = \text{affectual impact of } active\_object\_attribute, \text{ due to novel } current\_value\_comp_{ji} \text{ and reinforced } sign\_component_{ji}, \text{ on } c\_weight \text{ of } object\_attribute = F\left(\sum_{i=1}^{p} C(imp\_amod_i,\ imp\_mod_i)\right) \tag{37}$$

}
Else
{*active_object_attribute* is novel,
updated *object_m* = *C*(*object_m* ∪ (*active_object_attribute, current_value*))}}

vi. Assuming a parallel and/or distributed processing environment in the machine-mind, knowledge consistency necessitates updates to one instance of *object_m* to cascade through all its other active instances, and knowledge(*object*) and knowledge(context), as well. Ideally, long-term memory is updated at strategic intervals or "commit points".
vii. A novel *object_r*, or novel *active_object_attribute* or unusual (mismatch with an *object_m* or one anticipated (see (46)) *current_value* leads to the endogenous arousal of 'surprise', the degree of which contributes to the system's feelings, internal_state, tendency toward exploratory behaviour and sustenance of interest on *object_r*.

Thus, If *object_r* includes x_n ($0 \le x_n \le |object\_r|$) novel and/or x_u ($0 \le x_n \le |object\_r|$) unusual (*active_object_attribute, current_value*) tuples, then

Let,
the set of novel attributes = $object\_r_{xn}$; $|object\_r_{xn}| = x_n$,
the set of attributes with unusual $current\_values = object\_r_{xu}$; $|object\_r_{xu}| = x_u$,
$0 \le (x_n + x_u) \le |object\_r|$,
$object\_r_x = (object\_r_{xn} \cup object\_r_{xu})$,
Therefore, extending (26) using (23) and (27)–(37), gives,
[$\forall (active\_object\_attribute_i, current\_value_i) \in (object\_r_{xu} \vee object\_r_{xn})$, 1 <= i <= $(X_u \vee X_n)$]

- **degree of curiosity** aroused by $object\_r_{xn} \propto$ curiosity due to novel attributes

$$\propto C\left(\sum_{i=1}^{x_n}\left(\sum_{j=1}^{p_i}\left(imp\_amod_{ji} \cdot \sum_{k=1}^{q_{ji}} em\_value_{kji}\right)\right)\right) \tag{38}$$

- **degree of curiosity** aroused by $object\_r_{xu} \propto$ curiosity due to unusual attributes

$$\propto C\left(\sum_{i=1}^{x_u}\left(c\_weight_i. \quad \left(\sum_{j=1}^{p_i}\left(C\left(imp\_mod_{ji},\ imp\_amod_{ji}\right) \cdot \sum_{k=1}^{q_{ji}} em\_value_{kji}\right)\right)\right)\right) \tag{39}$$

and,
- **degree of curiosity** aroused by $object\_r_x$

$$\propto C(\text{curiosity due to } object\_r_{xn},\ \text{curiosity due to } object\_r_{xu}) \tag{40}$$

The weights (*c_weight*, imp_mod_{ji}, imp_amod_{ji}) in (38), (39) and (40) guide attention towards curiosity arising from the more poignant stimuli (this has been further explained in Section 3.2.3.)

3.2.2. Perception

"*The main function of system_1* (the experiencing self) *is to maintain and update a model of your personal world, which represents what is normal in it. The model is constructed by association that link ideas of circumstances, events, actions and outcomes that co-occur with some regularity, either at the same time or within a relatively short interval. As these links are formed and strengthened, the pattern of associated ideas comes to represent the structure of events in your life, and it determines your interpretation of the present as well as your expectations of the future… System_1 is adept at finding a coherent causal story that links the fragments at its disposal… Like ripples on a pond, activation spreads through a small part of the vast network of associated ideas.*" - [22]

Assimilating elements defined in the preceding section, we arrive at the following:

$$\begin{aligned}&\textbf{obj\_perception}(object,\ time,\ \text{internal\_state}(time),\ \text{context}(\text{region\_of\_interest}\ (modal\_limits,\ time_t),\ time))\\ &= F(object\_r_{time},\ time,\ \text{anticipation},\ (\text{active\_knowledge}(object,\ time,\ \text{internal\_state}(time),\\ &\quad \text{context}(\text{region\_of\_interest}(modal\_limits,\ time_t),\ time))))\end{aligned} \tag{41}$$

Where,

(a) $object\_r_{time} = object\_r$ at *time*.
(b) obj_perception summarizes system's interpretation of *object* behaviour($object\_r_{time}$) at *time*. It contributes to the analysis of the importance of *object* in context and consequently system's choices and requirements at ($time+1$).
(c) perception is an incremental phenomenon, and perception time-frame = time duration of a scenario = $[time_{t_0}, time_t]$
(d) active_knowledge represents granules of knowledge (e.g., context-sensitive knowledge(*object*)) in the system working memory at *time*. Typically,

$$\begin{aligned}&\textbf{active\_knowledge}(object,\ time,\ \text{internal\_state}(time),\ \text{context}(\text{region\_of\_interest}(modal\_limits,\ time_t),\ time))\\ &= \text{semantic network of } C(object\_m_{time}\\ &\cup\ \text{latent\_memories}(object,\ \text{internal\_state}\ (time),\ \text{context}(\text{scenario}(modal\_limits,\ time_{t_0},\ time_t),\ time))\\ &\cup\ \text{current\_experiences}\ (object\_r_{sc},\ system\_state_{sc},\ \text{context}(\text{scenario}\ (modal\_limits,\ time_{t_0},\ time_t),\ time)))\end{aligned} \tag{42}$$

In which,

i. $object\_m_{time}$ = section of *object_m* active or recalled at *time*, i.e., ($object\_m_{time} \subseteq object\_m$); it arises from the observation that not all of *object_m* may be active in the working memory of the system at *time*, typically equivalent to 'unpacking [19]' of *object_m* and consequently knowledge(*object*), across *time*; concentrating on recollections should awaken finer details [9] therein.
ii. *object_m* derives from (19) or (25), as is appropriate.
iii. latent_memories = semantic network of peripheral memories activated in response to *object_r*, the context and internal_state at *time*; these could be directly, metaphorically or cosmetically associated with *object* and the context. Very simply stated,

$$\begin{aligned}&\textbf{latent\_memories}(object,\ \text{internal\_state}(time),\ \text{context}(\text{scenario}\ (modal\_limits,\ time_{t_0},\ time_t),\ time)))\\ &\subseteq\ ((\text{knowledge}(object) - object\_m)\ \cup\ \text{knowledge}(\text{context}(\text{scenario}(modal\_limits,\ time_{t_0},\ time_t),\ time))\ \cup\ \ldots)\end{aligned} \tag{43}$$

iv. latent_memories and $object\_m_{time}$ include elements volitionally actuated as well as those (e.g., commonsense) triggered beyond conscious awareness.
v. current_experiences summarize experiences and realizations gleaned from the system's interactions with *object* in context during the perception time-frame; these enhance the system's repertoire of context-sensitive knowledge(*object*) and knowledge(context) as well. Thus, drawing from (17), (19) and (24),

$$\begin{aligned}&\textbf{current\_experiences}(object\_r_{sc},\ system\_state_{sc},\ (\text{context}(\text{scenario}(modal\_limits,\ time_{t_0},\ time_t),\ time))\\ &= \text{semantic network of } (real\_experiences,\ anticipations,\ ideas,\ counterfactuals,\ commonsense,\ domain\_knowledge,\\ &\ldots)\text{formed on } (object \in (\text{context}\ (\text{scenario}(modal\_limits,\ time_{t_0},\ time_t),\ time))\text{through perception time} - \text{frame}\\ &= \text{connected graph of (sets of } (active\_object\_attribute,\ current\_value,\ cu\_weight,\ reasons,\ belief,\ affects,\ldots)\\ &\text{constituting } (real\_experiences,\ anticipations,\ ideas,\ counterfactuals,\ commonsense,\ domain\_knowledge\ldots)\text{on}\\ &(object\ \in\ (context(scenario(modal\_limits,\ time_{t_0},\ time_t),\ time))\ \text{through perception time – frame}\end{aligned} \tag{44}$$

Where,

- ($active\_object$, $current\_value$) tuples constitute *object_r*s comprising $object\_r_{sc}$

$$\begin{aligned}&\boldsymbol{cu\_weight}(active\_object\_attribute)\ = F(c\_weight \text{ in } object\_m_{time},\ \text{subjective and objective}(current\_value)\\ &\text{revelations arising from an } object\_r)\end{aligned} \tag{45}$$

- *reasons* = logical support for (*active_object_attribute, current_value*) and (*object, active_object_attribute*, context, *cu_weight*) compatibility based, on analysis of $object\_m_{time}$ and impact of current_experiences involving other *objects* ∈ scenario.
- *belief* = *F*(belief in $object\_m_{time}$, confidence in truth of (*active_object_attribute, current_value, cu_weight, reasons*)).
- *affects* = *F*(affects in $object\_m_{time}$, curiosity and feelings aroused by *object_r*).
- updated *object_m* = *C*(*object_m* ∪ current_experiences)
- updated knowledge(context) = *C*(knowledge(context) ∪ updated *object_m*)
- updated knowledge(*object*) = *C*(knowledge(*object*) ∪ updated *object_m*)
- While knowledge(*object*), knowledge(context) and *object_m* are long-term memory constructs, active_knowledge, $object\_m_{time}$ and current_experiences are real-time components in the working memory.
- (44) echoes observations on the formation of experiences and the experiencing self in [22,40,42]

(e) $object\_m_{time}$ and latent_memories reflect the 'remembering self [22]', current_experiences depict the 'experiencing self'.

(f) The system juxtaposes $object\_r_{sc}$ and active_knowledge to predict *object* behaviour at *time*; thus,

$$\textbf{anticipation}(object\_r_{sc}, \text{active\_knowledge}(object, time, \text{internal\_state}(time), \text{context}(\text{region\_of\_interest}(modal\_limits, time_t), time)) = \text{set of}(object\_r_{ex}, ex\_belief, ex\_threshold)\text{tuples} \tag{46}$$

In which,

i. set of ($object\_r_{ex}$, *ex_belief, ex_threshold*) tuples = {($object\_r_{ex1}$, ex_belief_1, $ex\_threshold_1$), ($object\_r_{ex2}$, ex_belief_2, $ex\_threshold_2$),… ($object\_r_{exn}$, ex_belief_n, $ex\_threshold_n$)}, where $ex\_belief_i > ex\_belief_j$, ∀ $i < j$

ii. A ($object\_r_{exi}$, ex_belief_i, $ex\_threshold_i$) tuple depicts the i^{th} probable value ($object\_r_{exi}$) for $object\_r_{time}$, belief (ex_belief_i) in the expectation, and limits ($ex\_threshold_i$) of acceptability of $object\_r_{time}$ as equivalent to $object\_r_{exi}$, given context and internal_state.

iii. $belief_i$ and $ex\_threshold_i$ stem from current *object* behaviour ($object\_r_{sc}$), active_knowledge on the same and the internal_state of the system.

iv. In the initial stages of perception of *object* in context, anticipation equates to *object_m*. It is in the latter stages that current_experiences mould predictions.

v. If $object\_r_{time} = (object\_r_{exi} \pm ex\_threshold_i)$, where ($object\_r_{exi}$, $ex\_threshold_i$) ∈ anticipation, then,

{ex_belief_i is reinforced as the system's belief in $object\_r_{time}$, and
system *affects* are at par with active_knowledge on $object\_r_{exi}$}
Else
{$object\_r_{time}$ is novel or unanticipated,
belief in $object\_r_{time}$ = *F*(source of knowledge (e.g., hands-on experiences carry high belief [4])),
affects aroused draws from (40),
updated *object_m* (which simultaneously updates knowledge(*object*) and knowledge(context)) = *C*(*object_m* ∪ ($object\_r_{time}$, context, *belief, affects*,…)),
belief and *affects* for $object\_r_{time}$ contribute significantly to the formation of *obj_perception*, influence internal_state(*time* + 1) and its many derivatives}

g) In (44) and (46),

i. From (12), $object\_r_{sc}$ summarizes trivial and complex *object* behaviour across the perception time-frame and provides for the objective constituents of the system's current_experiences and anticipation of $object\_r_{time}$, i.e.,

$$\boldsymbol{object\_r_{sc}} = \int_{time_{t_0}}^{time_t} (object\_r_t \text{ in region\_of\_interest } (modal\_limits, t)\ dt) \tag{47}$$

In which,
- $object\_r_t = object\_r$ at $time = t$
- If $time_{t_0} = time$, then, $object\_r_{sc} = \Phi$, since *object_r* is a new entrant in the region_of_interest, and anticipation derives entirely from active_knowledge
- $object\_r_{time} \notin object\_r_{sc}$

ii. From (13), $system\_state_{sc}$ at *time* summarizes modulations in the system's internal_state across a perception time-frame; it contributes to the subjective components of perceptions underlying system's current_experiences on *object* in context.

$$\boldsymbol{system\_state_{sc}} = \int_{time_{t_0}}^{time_t} (\text{internal\_state}(t) \text{ in context}(\text{region\_of\_interest}(modal\_limits, t), \text{ time dt}) \tag{48}$$

i) While behaviour(*object*) describes *object*'s responses to context, obj_perception construes system's interpretation of behaviour(*object*). Thus, equating (14), (15), and (41) such that the perceiving system refers to itself as the input *object* (third-person perspective or self-reflective behaviour), we arrive at,

$$\begin{aligned}&\textbf{behaviour}(object,\ time,\ \text{context}(\text{scenario}(modal\_limits,\ time_{t_0},\ time_t), time-1), \text{internal\_state}(time-1))\\&\quad = F(\text{obj\_perception}(object,\ time-1, internal\_state(time-1),\\&\qquad \text{context}(\text{region\_of\_interest}(modal\_limits,\ time_t),\ time)))\end{aligned} \tag{49}$$

Using (4) and (41), we arrive at the following expression for the system's perception (reg_perception) of an entire region_of_interest at *time*,

$$\begin{aligned}&\textbf{reg\_perception}(\text{region\_of\_interest}(modal\_limits, time_t), time, \text{internal\_state}(time))\\&\quad = C(\cup_{i=1}^{n}(\text{obj\_perception}(object_i, time-1, \text{internal\_state}(time-1),\\&\qquad \text{context}(\text{region\_of\_interest}(modal\_limits,\ time_t),\ time))))\end{aligned} \tag{50}$$

where, |region_of_interest(*modal_limits, time$_t$*)| = *n objects.*

Thus, from (9) and (50), we arrive at,

$$\begin{aligned}&\textbf{context}(\text{region\_of\_interest}(modal\_limits,\ time_t), time)\\&\quad = F(\text{reg\_perception}(\text{region\_of\_interest}(modal\_limits,\ time_t),\ time,\ \text{internal\_state}(time)))\end{aligned} \tag{51}$$

From (8) and (50) arises the following formulation for the system's perception(sc_perception) of an entire scenario at *time*,

$$\begin{aligned}&\textbf{sc\_perception}(\text{scenario}(modal\_limits, time_{t_0}, time_t), time)\\&\quad = C(\textstyle\int_{time_{t_0}}^{time_t}(\text{reg\_perception}(\text{region\_of\_interest}(modal\_limits,\ t),\ time,\ \ \text{internal\_state}(time))dt)\end{aligned} \tag{52}$$

From (10) and (52)

$$\begin{aligned}&\textbf{context}(\text{scenario}(modal\_limits,\ time_{t_0},\ time_{t_n}),\ time)\\&\quad = sc\_perception(\text{scenario}(modal\_limits,\ time_{t_0},\ time_t),\ time)\end{aligned} \tag{53}$$

reg_perception and sc_perception influence concepts of context(region_of_interest, *time*+1), context(scenario, *time*+1), internal_state(*time*+1) and their derivatives; thereby affecting how the region_of_interest and current scenario appeal to the system, it's interest in the proceedings, urge to explore, etc. This observation finds application in Section 3.2.3.

The fact that current_experiences are continually updated through exposure of the system to contextual stimuli and consequent comprehension, reinforces the observation on perception (obj_perception, reg_perception, sc_perception) being an incremental phenomenon. The interdependence of obj_perception, reg_perception, sc_perception is evident in the cyclic formulations of (41), (50), and (52).

3.2.3. Attention dynamics

> *"The investment of attention improves performance in numerous activities… and is essential to some tasks, including comparison, choice, and ordered reasoning."* - [22]

> *"Early sensory processing within a single sense is modulated by information in, and attention, towards other senses"* – Charles Spence

Building on Inference_2 and Inference_3 in Section 3.1, attention emerges as one of the fundamental factors that select the '*n*' *objects* the system is interested in and consciously observes in a region_of_interest. Understandably, these *objects* are processed in parallel and co-operatively towards incremental perception of a region_of_interest and its derivatives. The following formulations deal with the role of attention in the instantiation of (32) through (36); plunging deeper into the finer constituents of mentalese [37]:

Let,

- $\boldsymbol{object\_r_{time_i}}$ = *object_r* of the ith object ($object_i$) in region_of_interest(*modal_limits*, *time*),
- $|object\_r_{time_i}| = \boldsymbol{Attr_{time_i}}$ (*active_object_attribute*, *current_value*) tuples
- |region_of_interest(*modal_limits*, *time*)| = $\boldsymbol{N_{time}}$ *objects*
- $\boldsymbol{object\_m_{time_i}} = object\_m$ of $object\_r_{time_i}$
- $\boldsymbol{A_{time}}$ = total deployable system-attention at *time*,
- $\boldsymbol{A_{time}(i)}$ = attention deployed for processing $object\_r_{time_i}$,
- $\boldsymbol{A_{time_{ji}}}$ = attention deployed for $active\_object\_attribute_{time_{ji}}$,
- $\boldsymbol{A_{time_{kji}}}$ = attention allocated for $modality\_act_{time_{kji}}$,
- $\boldsymbol{A_{time_{lkji}}}$ = attention bestowed on component$_l$ of $modality\_act_{time_{kji}}$,
- At the inter-object level, **active_attention** and **passive_attention** depict dynamic lists of objects processed within conscious awareness by the system or otherwise, respectively, where, for both lists, at any given time, $A_{time}(i) \geq A_{time}(j)$, $\forall\ i < j$. (Fig. 3 is a metaphorical depiction of these lists)

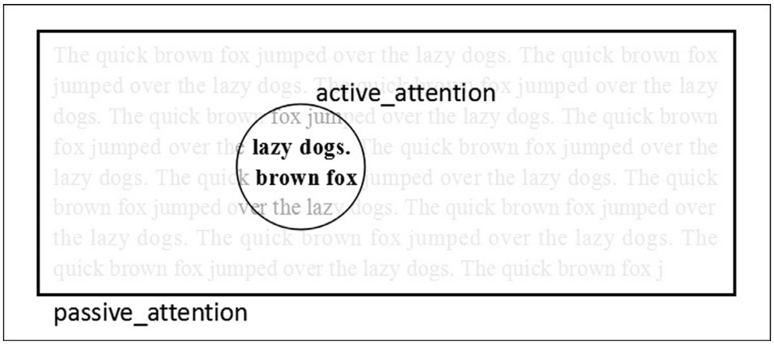


Fig. 3. Attention spotlight: depiction of grades of attention. [Gray-level intensity ∝ attention strength.].

- At the intra-object level, **act_obj_attention(object)** and **pas_obj_attention(object)** depict dynamic lists of active_object_attributes processed for an object within conscious awareness by the system or otherwise, respectively, where, for both lists, at any given time, $A_{time_{ji}} \geq A_{time_{ki}}$, $\forall\, j < k$.
- active_attention, act_obj_attention, passive_attention and pas_obj_attention are working memory constructs.
- Intuitively, the *objects* and *active_object_attributes* in the aforementioned lists act as pointers to associated semantic networks of active_knowledge and current_experiences; perception being a dynamic phenomenon, elements move between lists depending on the status of attention deployed. E.g.: 'Bursts of inspiration', 'epiphany' or 'Aha! Moments' arising from processing *objects* in passive_attention would induce high-impact affects in the system, eventually upgrading the responsible *objects* to the active_attention list.
- ***attn_threshold***(*time*) is the innate factor deciding the limits of conscious perception (wherein internal_state registers qualia for $object\_r_{timei}$ due to $A_{time}(i)$ [3]) at *time*, such that,

  If, ($A_{time}(i) \geq attn\_threshold(time)$), then, ($object_i \in$ active_attention) and system consciously processes $object\_r_{time_i}$
  Else, ($object_i \in$ passive_attention) and $object\_r_{time_i}$ is processed beyond conscious awareness

- ***attn_mod_threshold***(*modality_act*, *time*) is the intrinsic property determining the system's sensitivity to the presence of a particular modal signal (*modality_act*) exuding from an *object* at *time*,

  where, from (3), internal_state(*time*) draws from the system's health, inclusive of the status of its sensory receptors, and its willingness and need to receive *modality_act*, given the context,
  If ($\exists(modality\_act_{time_{kji}} \in active\_object\_attribute_{time_{ji}})$: ($A_{time_{kji}} \geq attn\_mod\_threshold\ (modality\_act_{time_{kji}},\ time)$))
  Then {($active\_object\_attribute_{time_{ji}} \in$ act_obj_attention(*object*)),
  system consciously processes $active\_object\_attribute_{time_{ji}}$}
  Else {($active\_object\_attribute_{time_{ji}} \in$ pas_obj_attention(*object*)),
  $active\_object\_attribute_{time_{ji}}$ is processed beyond conscious awareness}
  For $object\_r_{time_i}$ to be mapped to its *object_m*, at any given *time, (essential* of *object_m* ∈ act_obj_attention(*object*))

- ***system_threshold(time)*** = maximum number of elements that the system can consciously handle (parallely and cooperatively) at *time* = *F*(internal_state(*time*), importance and complexity of *objects* being processed at *time*). Therefore, a mechanism to prevent the system's attention from 'wandering' over to the less important would be,

  If (|active_attention| ≥ *system_threshold* (*time*)), then
  prune elements from tail end of active_attention until (|active_attention| ≤ *system_threshold*(*time*)) and insert into passive_attention

- For a dynamic region_of_interest, possibly ($N_{time} \neq N_{time-1}$), ($Attr_{time_i} \neq Attr_{(time-1)_i}$) and ($A_{time}(i) \neq A_{(time-1)}(i)$)

Therefore,
Stage 0: At $time = t_0$

From (3), internal_state(t_0) = *F*(*health, interests, urges, drives*,... elements that define the innate system self at t_0),
since, context(region_of_interest, t_0) = Φ; system's reactions are instinctive (∼ 'fast thinking') [22,28] to stimuli.
If,

total attention the system can deploy at $t_0 = A_0 = F$(internal_state (t_0)),
|region_of_interest(*modal_limits*, t_0)| = N_0

Then,

a) For **inter-object attention deployment** (attention per **object** ∈ region_of_interest(*modal_limits*, t_0)):
Attention deployed to $object\_r_{0_i} = A_0(i)$, such that,

$$\sum_{i=0}^{N_0} A_0(i) = A_0 \tag{54}$$

[(54) draws from [41] but introduces the role of the system self into the interpretation.]

b) For **intra-object attention deployment** (attention per modal constituent of an *object* ∈ region_of_interest(*modal_limits*, t_0); this builds on the objective and subjective impact of the components under consideration):

$$\text{Attention attracted by } component_l \text{ of } modality\_act_{0_{kji}} = A_{0_{lkji}} \propto ob\_value_{0_{lkji}} \\ \text{or, } A_{0_{lkji}} = (F(em\_value_{0_{lkji}}).ob\_value_{0_{lkji}}) \tag{55}$$

$$\text{Attention deployed for } modality\_act_{0_{kji}} = A_{0_{kji}} \propto \sum_{l=1}^{q_{kji}} A_{0_{lkji}} \\ \text{or, } A_{0_{kji}} = (F(imp\_amod_{0_{kji}}).\sum_{l=1}^{q_{kji}} A_{0_{lkji}}) \tag{56}$$

$$\text{Attention allotted for } active\_object\_attribute_{0_{ji}} = A_{0_{ji}} \propto \sum_{k=1}^{p_{ji}} A_{0_{kji}} \\ \text{or, } A_{0_{ji}} = (F(cu\_weight_{0_{ji}}).\sum_{k=1}^{p_{ji}} A_{0_{kji}}) \tag{57}$$

$$\text{Attention employed for } object\_r_{0_i} = \sum_{j=1}^{Attr_{0_i}} A_{0_{ji}} = A_0(i) \tag{58}$$

Multisensory information collected by the system over a fixation point [t_0, ($t_0+\Delta_0$)] is instinctively consolidated, by the system, into data packets which probe the system memory. These evoke primary emotions, mapping between an *object_r* and its *object_m*, preliminary interpretation of context, and recollections of associated experiences, commonsense and domain knowledge. These influence comprehension of region_of_interest and system behaviour. Data collected over time adds to these initial constructs towards enhanced understanding of scenario and improved system responses. Figs. 7 and 8 provide rough illustrations of these steps (the data structures shown therein are rough depictions of 'multimodal feature binding [8]').

Stage *n*: At $time = t_n$

While attention deployment and system behaviour at **stage 0** = *F*(multisensory stimuli and consequent innate emotions), that at **stage *n*** = *F*(multisensory stimuli, semantics, and learned, deliberative, reflective and self-conscious contemplation) [28,29];

From (11), internal_state(t_n) = *F*(internal_state(t_{n-1}), context(scenario, t_{n-1}));

From (10), context (scenario, t_n) = *C*(context(scenario, t_{n-1}), region_of_interest(*modal_limits*, t_n));

If, total attention the system can deploy at $t_n = A_n = F$(internal_state(t_n)), and |region_of_interest(*modal_limits*, t_n)| = N_n where,

- (From (8)) ***common*** = (region_of_interest(*modal_limits*, t_n) ∩ region_of_interest(*modal_limits*, t_{n-1})) = (set of common *objects* that help connect a series of dynamic region_of_interests); |*common*| = ***com_n***, where $1 \le com_n \le N_{n-1}$
- ***known*** = (set of (*objects* ∈ *common*) mapped to *object_m* using (19)); |*known*| = ***knw_n***
- ***comparable*** = (set of (*objects* ∈ *common*) mapped to *object_m* using (25)); |*comparable*| = ***comp_n***
- ***unknown*** = (set of (*objects* ∈ *common*) unmapped to *object_m* till t_{n-1}, and system is curious and has decided to continue exploration at t_n); |*unknown*| = ***uknw_n***

[From Section 3.2.1.1, the system creates knowledge(*object*) for *comparable* and *unknown* and updates knowledge(context) as well; the degree of system's interest directs its pursuit of such *objects* over time.]

- $com_n = knw_n + comp_n + uknw_n$
- ***new*** = (region_of_interest(*modal_limits*, t_n) – region_of_interest(*modal_limits*, t_{n-1})) = (set of *objects* introduced in region_of_interest at t_n); |*new*| = ***new_n***, where $0 \le new_n$;

while *common* represents *objects* that have undergone trials at semantic interpretation for the given context, *new* represents those that are yet to be tried.

- $N_n = com_n + new_n$
- ***left*** = (region_of_interest(*modal_limits*, t_{n-1}) – region_of_interest(*modal_limits*, t_n)) = (set of *objects* that existed in region_of_interest at t_{n-1} but have moved out at t_n); |*left*| = ***ex_n***, where $0 \le ex_n < N_{n-1}$

- ***distractions*** = (set of *objects* in region_of_interest at $t_{n\text{-}1}$ that system has marked irrelevant or unimportant or unidentifiable or a 'disturbance' and has consciously chosen not to process at t_n);

  $|distractions| = \boldsymbol{dist_n}$, where $0 \leq dist_n < N_{n\text{-}1}$;

- Attention allocated to *left* and *distractions* at $N_{n\text{-}1}$ is available for redistribution across N_n. (Ideally, frames for *left* and *distractions* are marked 'passive' in the system memory, to be upgraded to 'active' on requirement (e.g. re-entry into region_of_interest or offline reflection [5,6]).

  Then,

a) For **inter-object attention distribution**:

$$\text{Attention deployed to } object\_r_{n_i} = A_n(i), \text{ such that, } \sum_{i=0}^{N_n} A_n(i) = A_n \tag{59}$$

b) For **intra-object attention deployment**:

$$\text{Attention attracted by } component_l \text{ of } modality\_act_{n_{kji}} = A_{n_{lkji}} \propto ob\_value_{n_{lkji}}$$
$$\text{or, } A_{n_{lkji}} = (F(em\_value_{n_{lkji}}).ob\_value_{n_{lkji}}) \tag{60}$$

Now,

- For *objects* ∈ *new*,

$$\text{Attention deployed for } modality\_act_{n_{kji}} = A_{n_{kji}} \propto \textstyle\sum_{l=1}^{q_{kji}} A_{n_{lkji}}$$
$$\text{or, } A_{n_{kji}} = (F(imp\_amod_{n_{kji}}). \textstyle\sum_{l=1}^{q_{kji}} A_{n_{lkji}}) \tag{61}$$

$$\text{Attention allotted for } active\_object\_attribute_{n_{ji}} = A_{n_{ji}} \propto \textstyle\sum_{k=1}^{p_{ji}} A_{n_{kji}}$$
$$\text{or, } A_{n_{ji}} = (F(cu\_weight_{n_{ji}}). \textstyle\sum_{k=1}^{p_{ji}} A_{n_{kji}}) \tag{62}$$

$$\text{Attention employed for object\_r}_{n_i} \in \text{new} = \sum_{j=1}^{\text{Attr}_{n_i}} A_{n_{ji}} = A_n(i) \tag{63}$$

$$\text{Total attention deployed for new} = A_{n_{new}} = \sum_{i=1}^{new_n} A_n(i) \tag{64}$$

- For *objects* ∈ *common*,

$$\bullet\, \boldsymbol{D_{imp_n}}(i) = \text{degree of importance or interest and understanding of } i^{th}\ object \in \text{context}(\text{scenario}, t_n)$$
$$= F(\text{obj\_perception}\big(object, t_{(n-1)}, \text{internal\_state}\big(t_{(n-1)}\big), \text{context}\big(\text{region\_of\_interest}, t_{(n-1)}\big)\big), attn\_threshold(t_n),$$
$$\text{knowledge}(object), \text{knowledge}(\text{context}), \text{sc\_perception}\big(\text{scenario}(modal\_limits, time_{t_0}, time_t), t_{(n-1)}\big), \ldots) \tag{65}$$

$$\bullet\, \boldsymbol{D_{imp_{att\,jn}}}(i) = \text{degree of importance of } active\_object\_attribute_{n_{ji}} \text{ in describing } i^{th}\ object \in \text{context}(\text{scenario}, t_n)$$
$$= F(\text{knowledge}(object), \text{knowledge}(\text{context}), \text{sc\_perception}\big(\text{scenario}(modal\_limits, time_{t_0}, time_t), t_{(n-1)}\big),$$
$$cu\_weight_{n_{ji}}, \text{novelty of } active\_object\_attribute_{n_{ji}}, \text{ variance of } current\_value_{n_{ji}} \text{ from anticipation},$$
$$attn\_mod\_threshold\big(modality\_act_{n_{kji}}, t_n\big) \forall\, modality\_act_{n_{kji}} \in active\_object\_attribute_{n_{ji}}, \ \ldots) \tag{66}$$

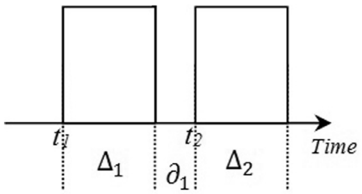
- $D_{imp_n}(i)$ and $D_{imp_{att\,jn}}(i)$ incrementally relate 'meanings', 'context' and 'attention' [23] to guide concentration towards the more important, novel and interesting *objects* and their attributes in the region_of_interest.
  Therefore,

$$\text{Attention deployed for } modality\_act_{n_{kji}} = A_{n_{kji}} \propto \textstyle\sum_{l=1}^{q_{kji}} A_{n_{lkji}}$$
$$\text{or, } A_{n_{kji}} = (C(imp\_amod_{n_{kji}}, imp\_mod_{n_{kji}}). \textstyle\sum_{l=1}^{q_{kji}} A_{n_{lkji}}) \tag{67}$$

$$\text{Attention allotted for } active\_object\_attribute_{n_{ji}} = A_{n_{ji}} \propto \textstyle\sum_{k=1}^{p_{ji}} A_{n_{kji}}$$
$$\text{or, } A_{n_{ji}} = (D_{imp_{att\,jn}}(i). \textstyle\sum_{k=1}^{p_{ji}} A_{n_{kji}}) \tag{68}$$

$$\text{Attention employed for } object\_r_{n_i} \text{ in } common = A_n(i) \propto \textstyle\sum_{j=1}^{Attr_{n_i}} A_{n_{ji}}$$
$$\text{or, } A_n(i) = (D_{imp_n}(i). \textstyle\sum_{j=1}^{Attr_{n_i}} A_{n_{ji}}) \tag{69}$$

$$\text{Total attention deployed for } common = A_{n_{common}} = \sum_{i=1}^{com_n} A_n(i) \tag{70}$$



t_i	Start of i^{th} fixation-point
Δ_i	Duration of i^{th} fixation-point
∂_i	Duration of i^{th} saccade

Fig. 4. Interpretation of fixation-point and saccade.

- For ***objects*** ∈ ***left***,

$$\begin{aligned}&\text{Total attention deployed for } left \text{ at } t_{(n-1)} = A_{(n-1)_{left}} = \textstyle\sum_{i=1}^{ex_n} A_{(n-1)}(i)\\ &\text{where, } i \text{ denotes} (object\_r_{(n-1)_i} \in left)\end{aligned} \tag{71}$$

- For ***objects*** ∈ ***distractions***,

$$\begin{aligned}&\text{Total attention deployed for } distractions \text{ at } t_{(n-1)} = A_{(n-1)_{dist}} = \textstyle\sum_{i=1}^{dist_n} A_{(n-1)}(i)\\ &\text{where, } i \text{ denotes} (object\_r_{(n-1)_i} \in distractions)\end{aligned} \tag{72}$$

Therefore, from (64) and (70),

$$A_n = A_{n_{new}} + A_{n_{common}} \tag{73}$$

In (71) and (72), $A_{(n-1)}(i)$ relates to (63) or (69), as is appropriate at $t_{(n\text{-}1)}$, and

$$A_n \text{ is inclusive of } \left(A_{(n-1)_{dist}} + A_{(n-1)_{left}}\right) \tag{74}$$

The rationale herein draws from the integrated-differentiated view of multimodal input processing [8,43] and illustrate the interdependence between attention and perception of real-world events. The atomic object-descriptors in (55) and (60), track system's innate responses to stimuli, while the modal components in (56), (61) and (67) facilitate reasoning of disparities between an *object_r* and its *object_m*. These parameters drive system's feelings, interest and curiosity in *object*, and accordingly modulate attention. (57), (62) and (68) guide extraction of and attention towards consequential context-sensitive attributes at run-time, subsequently evoking memory management schemes (e.g., pruning less-important attributes from act_obj_attention(*object*))). The model optimizes between fine-grained, (analyses of modal stimuli) and coarse-grained perception (over *active_object_attributes*), for novel and regular *object_r*, respectively – directing greater attention for enhanced sensitivity to modulations in stimuli and improved comprehension in the former case. (Detailed steps of effective attention scheduling are beyond the scope of this article). The formulations encode reasons for perception, attention categories [2] and support reinforcement. (55) through (64) deal with instinctive reactions to new stimuli, thereby contributing to the system's ' fight or flight [22]' decisions or 'alarmer [29]' systems. Definitions (54) through (74) augment the concepts of attention dynamics and perception in [41] through consideration of multimodal stimuli and the role of the system's sense of self (choices, affects, curiosity, etc.).

The following section describes the integration of all the defined parameters into a Z*-number based model of thinking for a social cognitive system [5,6]. Fig. 1 through Fig. 8 depict pictorial summaries of the model, Table 1 summarizes definitions, and Table 2-Fig. 10 and Table 3-Fig. 12 illustrate sets of system-execution-human-responses.

3.3. An algorithm for 'thinking'

Note: Though the terms "fixation-point" and "saccade" pertain to vision-inputs, the proposed procedure uses them in the generic sense of – point of focus of active-attention in the current region_of_interest (irrespective of sensory input-type, e.g., in the direction of a sound or an odour) and time between two fixation-points, respectively. While a fixation-point corresponds to the time during which the system accepts sensory inputs, a saccade represents the time during which the system processes the accumulated input. [Refer Fig. 4 for an illustration of the interpretation.]

Algorithm 1. Activation of thoughts in a computational mind during comprehension of a real-world scenario, where Z*-numbers serve as perceptual symbols [7] of active thoughts.

Input: A real-world scenario – this could represent an external world phenomenon or a system-mind element
Output: Sensorimotor responses, active_knowledge graphs of granules of comprehension, updated knowledge-networks.
Assumptions about system configuration:

(a) It can map its feelings to natural language expressions or mentalese
(b) It thinks in linguistic expressions which are converted into Z*-number equivalents during inter-thought processing operations; Z*-information = semantic networks of objective and subjective information
(c) Z*-number based operators are well-defined and corresponding hardware units are functional
(d) It has a multimodal sensory system in place

(e) Background processes – in the order of memory management, reinforcement cycles, consolidation of new and existing experiences and knowledge, surprise and curiosity handling, preventing combinatorial thought-explosions, resource arbitration, process scheduling, etc. – are active
(f) Typically, repeated reinforcement over a threshold places an (*action, reaction*) or (*situation, reaction*) tuple under instinctive reactions
(g) The architecture supports simultaneous serial and co-operative parallel processing.

Fig. 5 illustrates our conceptualization of the macro-steps of thinking in a cognitive system, where contemplation involves objective and subjective information processing across all the different levels [28,29] of a working mind. We do not claim our design to be an accurate and exhaustive list of steps underlying real-world comprehension, but it nonetheless is an attempt at deconstructing the phenomenon of 'thinking' . Some crucial questions that emerge here are, how do we, a) relate qualia to linguistic expressions, b) compute with word-senses to form new expressions, and c) what influences the contents of $object\_m_{time}$ and latent_memories at *time*. Fig. 6 highlights different processing modes across Algorithm 1 [where, 'words' denote text/audio/mentalese inputs, 'frame/terminal/slots' denote memory elements, and a saccade is equivalent to one iteration through the algorithm]. Figs. 7 and 8 illustrate control flow through the procedure and a sample attention distribution scenario, respectively. Section 4 presents results of dry-runs through the conceptualized procedure and correspondence studies against human-subject responses.

Properties of Algorithm 1:

(a) The motto of the framework is reflected in the words "*reached… ingenious solutions to… problems through a cycle of conscious thought, unconscious thought, illumination… and verification.*" [27]. The defined procedure thus, approximates to a cycle of: [raw sensory information input → (*natural language* | *mentalese*) description → Z*-information equivalent conversion → Z*-information processing and result generation → (((*natural_language* | *mentalese*) equivalent) *sensorimotor_commands* …) → system responses → raw sensory information (*request* | *input*) → …]
(b) It is incremental-iterative, and a conjunction of Shiffrin and Scheneider's views [39] on endogenous deductions, and Treisman's and Norman's theories [32,43] of selective attention and perception. It incorporates philosophies of the continually updating 'experiencing self' [22,40] and 'never-ending' learning [30].
(c) The layers of active-mind processes in [28,29] and the need for 'multimodal feature binding [8]' are explicitly covered.
(d) It emulates 'fast thinking [22]' when it yields to instinctive reactions, and 'slow thinking [22]' when deliberation, reflection and self-consciousness come to the fore.
(e) Processes involve both 'sensory' and 'semantic' data packets across short-term (sensory, working) and long-term (procedural, declarative) memories.
(f) Probing the system-internal environment equates to micro-thinking or reflection during a macro-contemplation step.
(g) The role of the self – in terms of exercising volition and consolidation of experiences – is an important component of the algorithm.
(h) Attention dynamics, as a *F*(perception, volition, instinct, requirement), is the system's mechanism of dealing with the deluge of multisensory real-world information.
(i) The periphery of attention (∼ region_of_interest), defined by *modal_limits*, is dynamic. 'Sustained [16]' active attention intuitively leads to smaller, precise margins while exploratory cognitive processes induce larger areas. [Refer Fig. 3 for a pictorial depiction of attention spotlights.]
(j) Unidentified objects or events in the region_of_interest arouse 'intrinsic motivation' [16] to seek answers. Instantiation of interrogative mentalese and their sensorimotor counterparts influence volitional attention deployment [23] and exploratory behaviour of the system over the region_of_interest.
(k) Through subtle modulations in time_t in the definition of region_of_interest, through ($time_t \neq time$) considerations, the system travels back and forth across scenes or thoughts during reflection.
(l) Frames, terminals and slots in [28] roughly translate into object, attributes and values respectively, where affects and beliefs influence the weights of the connecting edges, and context and time bind a number of such connected graphs.
(m) A crucial design concern is the determination of the duration of a fixation point ($= \Delta_{time_t}$), such that disparities in multimodal feature binding due to fundamental differences in the nature of modalities (e.g., differences in velocities of light and sound waves) or simultaneous events (e.g., fall and thud) can be handled in real-time during a saccade.
(n) The influence of 'subjective time [2]' has not been explicitly dealt with.
(o) The model does not categorically depict instantiation of counterfactuals. These may be envisioned as spin-offs of reflection.
(p) In the current design-stage, the algorithm does not expand on the steps underpinning translation from Z*-numbers to mentalese and Z*-based operations, conversion from semantic to sensory data-packets, memory and affect management, 'multi-realm [28,29]' thinking, resilience-strategies to counter 'thinking break downs [29]', interactions between active and passive Z*-numbers and cross-object Z*-information interactions. Z*-information operators for consolidation, updating and reasoning need to be designed as well.
(q) The model assumes intrinsic rationalism. Identification and handling of biases is an important design concern.
(r) The time complexity of the algorithm is *F*(complexity of region_of_interest, system's interest in it). Greater the complexity of region_of_interest and greater the system's interest, larger is the number of iterations required. Memories

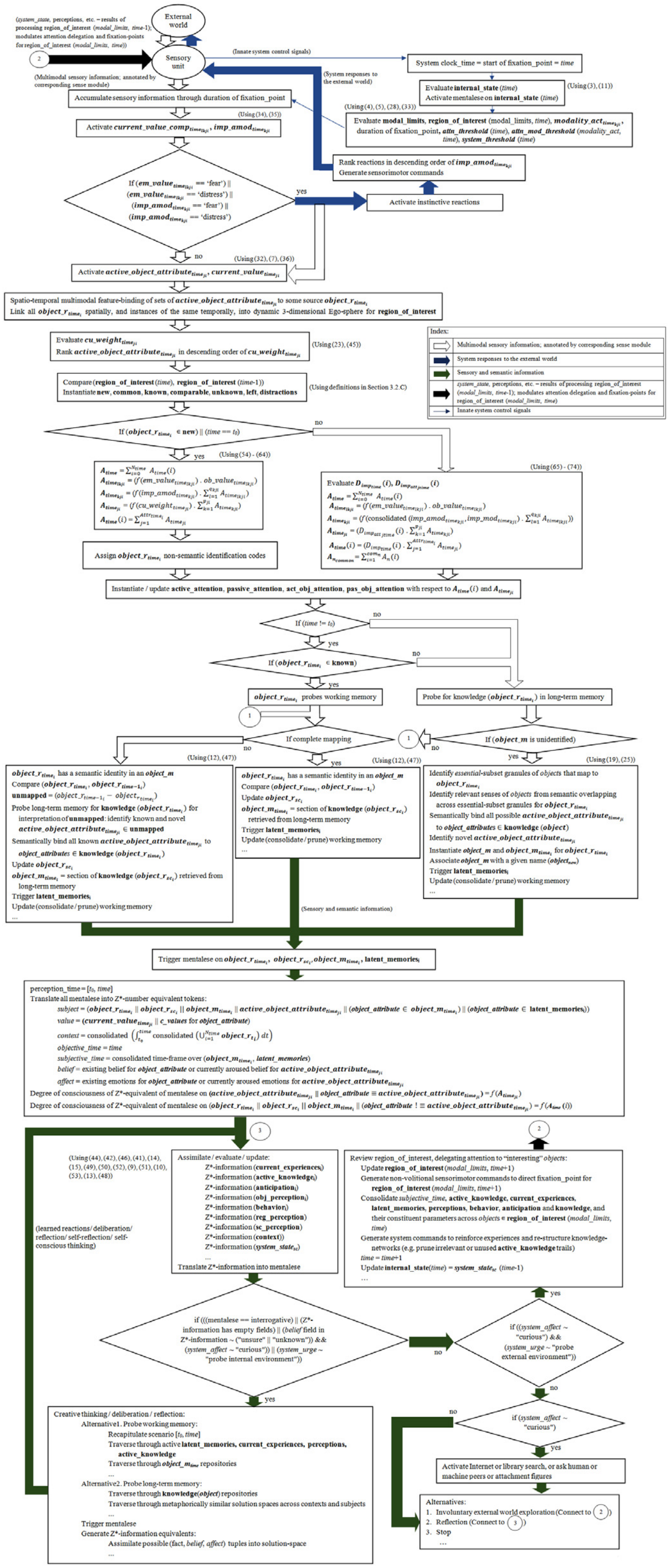


Fig. 5. Flowchart of contemplation.

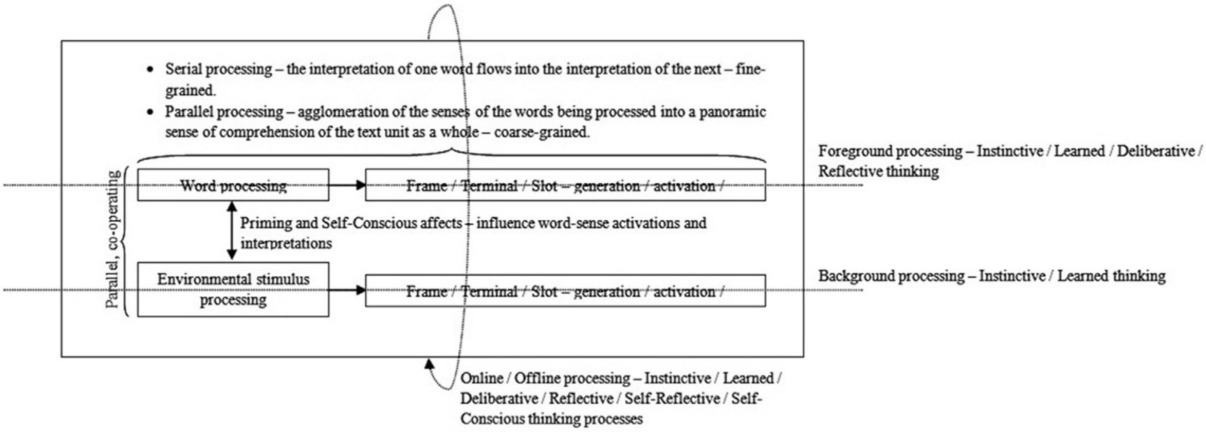


Fig. 6. Processing modes [5,6] across Algorithm 1.

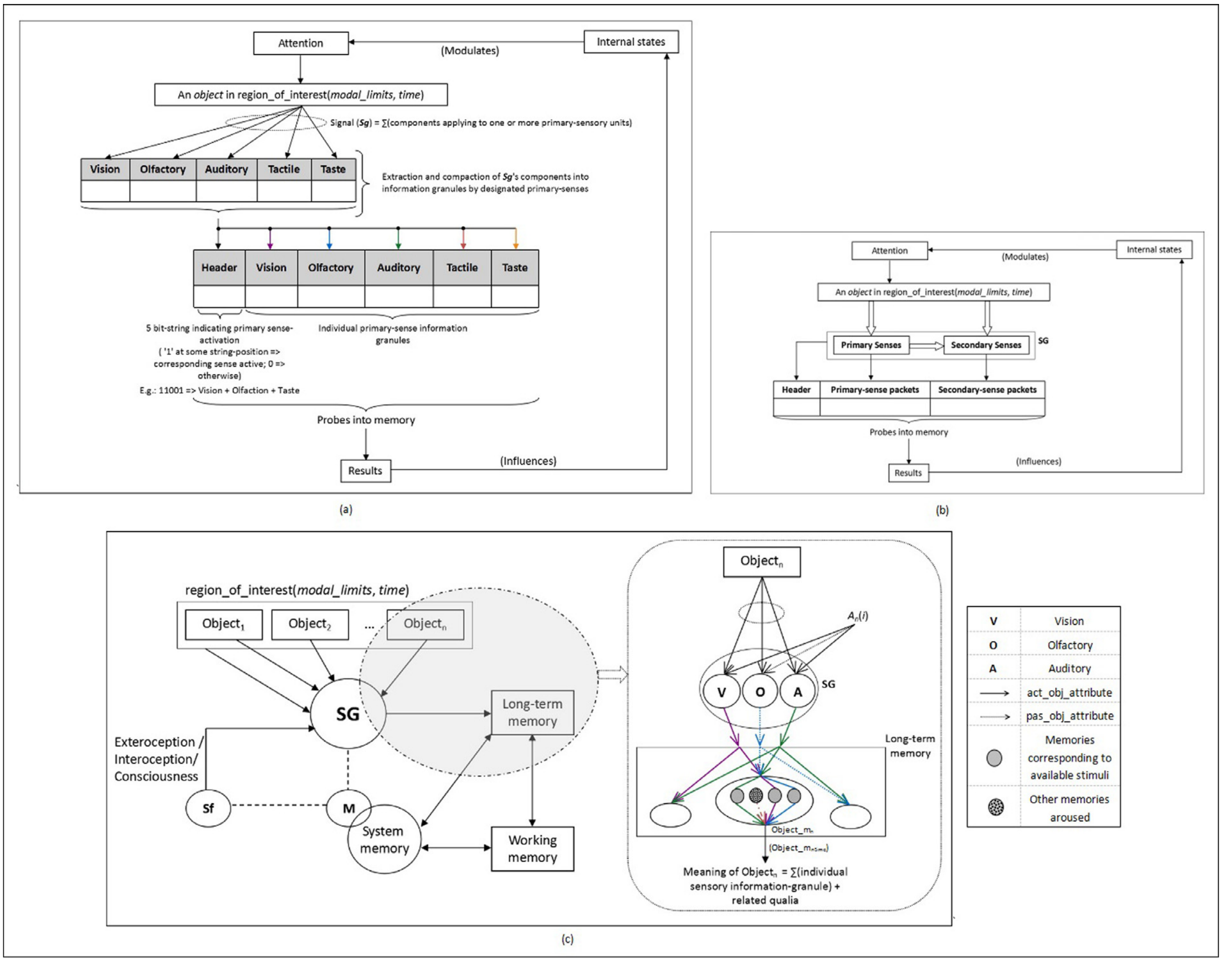


Fig. 7. Pictorial summary of the arousal of memories and thoughts.

[(a) Primary multisensory signals from object are assimilated into a sensory data-packet which queries the system long-term memory for associated semantic recollections. The Header node of the data-packet summarizes information on the signals available and supports 'multimodal feature binding [8]'. A number of such packets is formed for a region_of_interest;

(b) Complete data-packets include primary and secondary multimodal signal information;

(c) With reference to the machine-mind framework in [5,6], the Sensory Gateway (**SG**) module instantiates sensory data-packets which, in sync with the Self (**Sf**) and Manager (**M**) modules, probe the system memory. This activates *object_r*, arouses emotions and active_knowledge.]

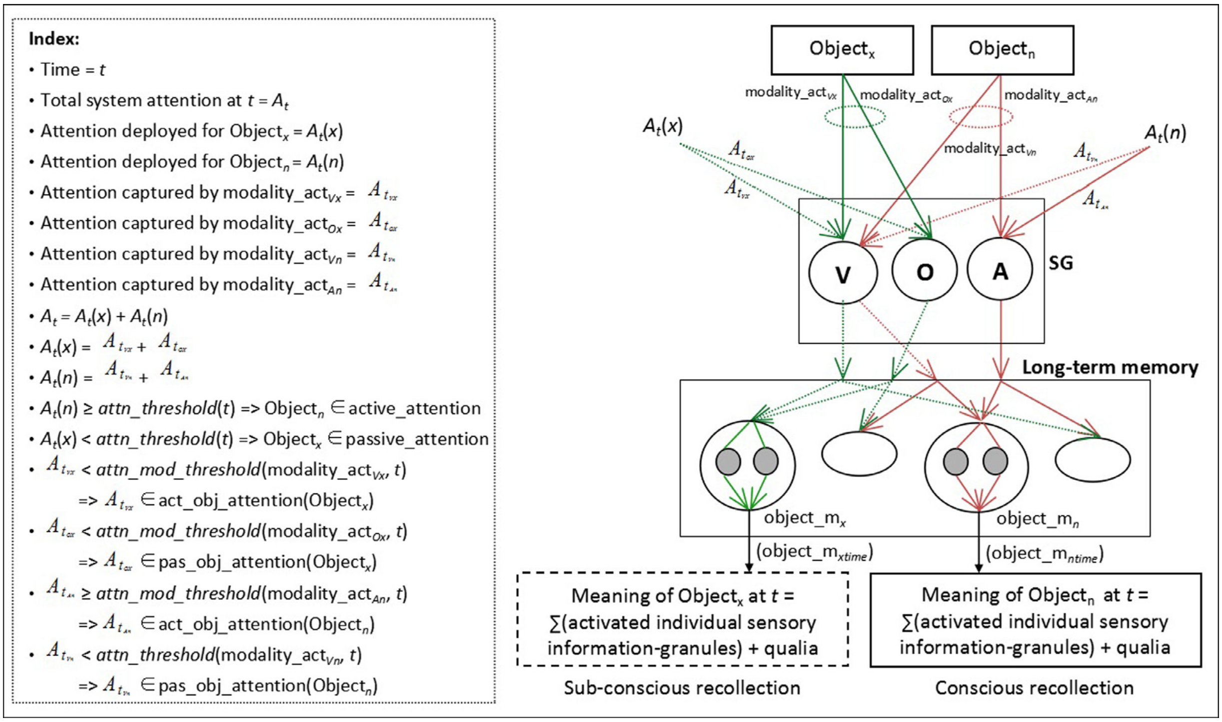


Fig. 8. Attention deployment across objects and their constituents. [Notations follow those in Fig. 7.].

Fig. 9. Test image 1. (Source: Internet).

aroused could adversely affect the time-taken if a combinatorial explosion of thoughts is activated. Mechanisms to counter such, is thus an important system-design issue.

4. Results

This section records anticipated system-responses (dry-runs through the conceptualized model) and their correspondences with human-subject answers to input real-world information.

Assumption. The system can recognize popular animals and elements and possesses multimodal knowledge-networks of their very basic properties (features, habits and locations).

4.1. Result_1

Input: Fig. 9.

Output: System's responses are summarized in Table 2, while human-subject answers are enumerated in Fig. 10 (the X-axis lists responses and the Y-axis lists the number subjects who responded accordingly). 12 erudite human-subjects were shown Fig. 9 and were asked to summarize their thought processes during interpretation of the image. The words uttered, expression used, and the number of individuals using them were recorded. Our aim was to see if the system-outcome

Table 2
Summary of dry-run through procedure in response to Fig. 9.

Time	Processes

Fixation-point: $[t_0, (t_0 + \Delta_0)]$
Saccade: $[(t_0 + \Delta_0), (t_0 + \Delta_0 + \partial_0)]$
	• The system is presented with |**region_of_interest**(*modal_limits, t_0*)| = 4 (2 foreground and 2 background objects);
	• **internal_state**(t_0) and its derivatives are evaluated; *internal_state* (t_0) = base system self
	• Multimodal information (*active_attributes* and corresponding *current_values*) from region_of_interest is collected over Δ_0;
	• Attributes or features are bound to define four ***object_r***$_{\mathbf{0_i}}$ slots;
	• An ego-sphere for region_of_interest (*modal_limits, t_0*) is instantiated; [ego-sphere = a mental image of the input-picture]
	• All objects are placed in ***new***;
	• Attention deployment follows (54) through (58); [foreground receives greater attention than background]
	• Each *object_r*$_{0_i}$ is assigned a non-semantic identification code <format: *object$_i$*, where *i* => the i^{th} object>;
	• **active_attention** = [*object$_1$*, *object$_2$*, *object$_3$*, *object$_4$*]; (*object$_1$*, *object$_2$* imply foreground objects, *object$_3$*, *object$_4$* imply background objects)
	• *object_r*$_{0_i}$ probe long-term memory, and the system attempts mapping objects to respective *object_m$_i$*;
	[*object$_1$*, *object$_2$* are identified as* '*tiger*' *and* '*crocodile*' *respectively*; *object$_3$*, *object$_4$* *are identified as* '*water-body*']
	• ***object_m***$_{\mathbf{0_i}}$ (= basic properties of the identified objects) and **latent_memories** (= personal encounters, metaphors etc.) pertaining to *objects* are fetched into working memory;
	• Mentalese pertaining to *object_r*$_{0_i}$, *object_m*$_{0_i}$, latent_memories are actuated in working memory;
	[*e.g.*, "*a Royal Bengal tiger*", "*tigers roar*", "*tiger found in Sunderbans, Ranthambore*", "*a crocodile*", "*saw crocodiles in Sunderbans*", "*tiger and crocodiles are carnivores*", "*tiger and crocodile in water-body*", "*tigers and crocodiles can swim*", "*crocodile is a reptile*", "*rivers, seas, oceans*", "*tigers and crocodiles found in zoo*"]
	• Mentalese are translated into their Z*-number equivalents;
	[e.g., Z_i = <picture, current, Royal Bengal tiger, definitely, <fear, high, +>>, Z_j = <picture, current, crocodile, probably, <fear, high, +>>, Z_k = <water-colour in picture, current, greyish-blue, possibly, <serenity, moderate-high, +>>]
	• System attempts evaluation of preliminary sense of *context, obj_perception, reg_perception, sc_perception, anticipation*;
	[*context*: input-picture; *obj_perception*: Tigers and crocodiles are found in Sunderbans, carnivorous animals, they can swim; *sc_perception*: Is this a picture of Sunderbans or a zoo? Which water-body?]
	• System evaluates ***system_state***$_{sc}$($\boldsymbol{t_0}$); [*system_state* (t_0) = curious about the meaning of the picture, probe picture again]
	• The ***system_affect*** = "curious" and ***system_urge*** = "probe external environment":
	  ○ fixation_point: macroscope around foreground objects = focus on background area around object;
	  ○ Duration of fixation_point at t_1 (= Δ_1) defined;
	  ○ Saccade activated for tuning system's attention to fixation_point and its periphery

Fixation-point: $[t_1, (t_1 + \Delta_1)]$ Saccade: $[(t_1 + \Delta_1), (t_1 + \Delta_1 + \partial_1)]$	• The system is presented with |**region_of_interest**(*modal_limits, t_1*)| = 4 (2 foreground and 2 background objects); • **internal_state**(t_1) = integration of internal_state(t_0), *system_state* (t_0) • Multimodal information (*active_attributes* and *corresponding current_values*) from the region_of_interest is collected over Δ_1; • Attributes or features are bound to define four ***object_r***$_{\mathbf{1_i}}$ slots: out of which two slots point to objects processed in the preceding state; • An ego-sphere for region_of_interest (*modal_limits, t_1*) is instantiated; • All objects are placed in ***common***; • Attention deployment follows (59) through (74); [the background is deployed greater attention than foreground] • The *object_r*$_{1_i}$ pertaining to background is assigned a non-semantic identification code <*object$_3$*, *object$_4$*>; • **active_attention** = [*object$_3$*, *object$_4$*, *object$_1$*, *object$_2$*]; • objects completely map to data in the working memory; • ***object_m***$_{\mathbf{1_i}}$ (= properties of the identified objects) and **latent_memories** (= personal encounters, metaphors etc.) pertaining to objects are fetched into working memory; • Mentalese pertaining to *object_r*$_{1_i}$, *object_m*$_{1_i}$, latent_memories are actuated in working memory; [*e.g.*, "*a Royal Bengal tiger*", "*tigers roar*", "*tiger found in Sunderbans, Ranthambore*", "*a crocodile*", "*saw crocodiles in Sunderbans*", "*tiger and crocodiles are carnivores*", "*tiger and crocodile in water-body*", "*tigers and crocodiles can swim*", "*crocodile is a reptile*", "*rivers, seas, oceans*", "*tigers and crocodiles found in zoo*", "*the water for tiger is upstream*", "*the water for crocodile is downstream*"] • Mentalese are translated into their Z*-number equivalents; [e.g., Z_i = <picture, current, Royal Bengal tiger, definitely, <fear, high, +>>, Z_j = <picture, current, crocodile, probably, <fear, high, +>>, Z_k = <water-colour in picture, current, greyish-blue, possibly, <serenity, moderate-high, +>>, Z_l = <water-flow, current, different through picture, definitely, <curious, high, +>>] • System attempts evaluation of preliminary sense of *context, obj_perception, reg_perception, sc_perception, anticipation*; [*context*: input-picture; *obj_perception*: Tigers and crocodiles are found in Sunderbans, carnivorous animals, they can swim, water-flow for tiger and crocodile is different; *sc_perception*: Is this a picture of Sunderbans or a zoo? Which water-bodies? Tiger and crocodile on different water-bodies?] • System evaluates ***system_state***$_{sc}$($\boldsymbol{t_1}$); [*system_state* (t_1) = curious about the meaning of the picture, stop]
Outcome: *context*: input-picture; *obj_perception*: Tigers and crocodiles are found in Sunderbans, carnivorous animals, they can swim, water-flow for tiger and crocodile is different; *sc_perception*: Is this a picture of Sunderbans or a zoo? Which water-bodies? Tiger and crocodile on different water-bodies?	

mapped to some/all of the words. The system-outcome does emerge as an approximation of human-responses and the thought-process is definitely one out of numerous possibilities.

4.2. Result_2

Input: Image depicted in Fig. 11.

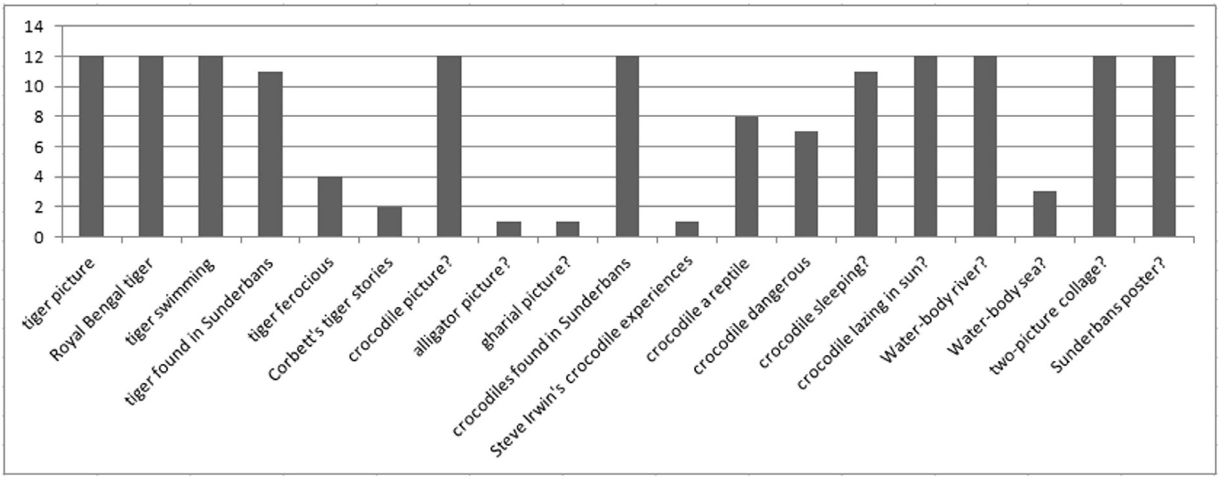


Fig. 10. Human-subject responses to Fig. 9.

Fig. 11. Test image 2. (Source: Internet).

Output: System's responses are summarized in Table 3, while human-subject answers are enumerated in Fig. 12 (the X-axis lists responses and the Y-axis lists the number subjects who responded accordingly). 12 erudite human-subjects were shown the image in Fig. 11 and were asked to summarize their thought processes during interpretation of the image. The words uttered, expression used, and the number of individuals using them were recorded. Our aim was to see if the system-outcome mapped to some of the words. The system-outcome here too emerges as an approximation of human-responses and the thought-process is certainly one out of numerous possibilities.

Observations pertaining to Result_1 and Result_2:

(a) None of the human-subjects were able to deconstruct their thoughts to atomic processes. We thus relied on verbal utterances and the nature thereof to map system-responses.
(b) In the first example, the system chooses to stop probing after the second iteration, but it could nonetheless continue probing the internal or the external environment. In the second example the system decides to actuate an Internet search for more information, while it could probe the picture again or ask its attachment-figures [28,29].
(c) Tables 2 and 3 demonstrate just one way of thinking. The system could take any one of all possible paths. The fact that the algorithm cover some mechanisms of human thought processes serves as a first test of its correctness.

4.3. Analysis of the model

[*Refer* Section 3.3 *for properties of the conceptualized algorithm*.]

(a) The framework is anthropomorphic, drawing from introspections, and the psychology and neuroscience of contemplation in human beings.
(b) The conceptualized model on 'thinking' is not exhaustive. It leaves many issues unresolved as well as requires answers to many fundamental questions on contemplation before it can be entirely realized. Questions of importance are: the points of activation of consciousness and influence thereof, all the different factors that influence attention

Table 3
Summary of dry-run through procedure in response to Fig. 11.

Time	Processes
Fixation-point: $[t_0, (t_0 + \Delta_0)]$ Saccade: $[(t_0 + \Delta_0), (t_0 + \Delta_0 + \partial_0)]$	• The system is presented with $\lvert$**region_of_interest**(*modal_limits, t_0*)$\rvert = 1$ (1 foreground object); • **internal_state**(t_0) and its derivatives are evaluated; [*internal_state* (t_0)=base system self] • Multimodal information (active_attributes and corresponding *current_values*) from the region_of_interest is collected over Δ_0; • Attributes or features are bound to define one ***object_r***$_{\mathbf{0}_i}$ slot; • An ego-sphere for region_of_interest (*modal_limits, t_0*) is instantiated; • ***object_r***$_{\mathbf{0}_1}$ are placed in ***new***; • Attention deployment follows (54) through (58); [*object_r*$_{0_1}$ is bestowed complete attention] • *object_r*$_{0_1}$ is assigned a non-semantic identification code < *object$_1$* >; • **active_attention**=[*object$_1$*] • *object_r*$_{0_1}$ probes long-term memory, and the system attempts mapping it to respective *object_m$_i$*; [*object$_1$* is identified as a cat] • ***object_m***$_{\mathbf{0}_1}$ (= basic properties of the identified object) and **latent_memories** (= personal encounters, metaphors etc.) pertaining to objects are fetched into working memory; • Mentalese pertaining to *object_r*$_{0_1}$, *object_m*$_{0_1}$ latent_memories are actuated in working memory; [*e.g.*, "*a cat*", "*a white cat*", "*cat with one blue eye*", "*cat with one yellow eye*"] • Mentalese are translated into their Z*-number equivalents; [e.g., Z_i=<picture, current, cat, definitely, <happy, moderate, +>>, Z_j=<cat-color, current, white, definitely, <happy, moderate-high, +>>, Z_k=<cat one-eye-colour in picture, current, blue, definitely, <happy, moderate-high, +>>, Z_l=<cat one-eye-colour in picture, current, yellow, definitely, <fear, moderate-high, +>>] • System attempts evaluation of preliminary sense of *context, obj_perception, reg_perception, sc_perception, anticipation*; [*context*: input-picture; *obj_perception*: beautiful white cat, cat has one blue eye and one yellow eye; *sc_perception*: Different coloured eyes is natural? Only in cats?] • System evaluates ***system_state$_{sc}$***(***t_0***); [*system_state* (t_0)=curious about eye-colour, wish to know more] • The ***system_affect***="curious" and ***system_urge***="Internet search"
Outcome: [*context*: input-picture; *obj_perception*: white cat with one blue eye and one yellow eye; *sc_perception*: Different coloured eyes is natural? Only in cats?]	

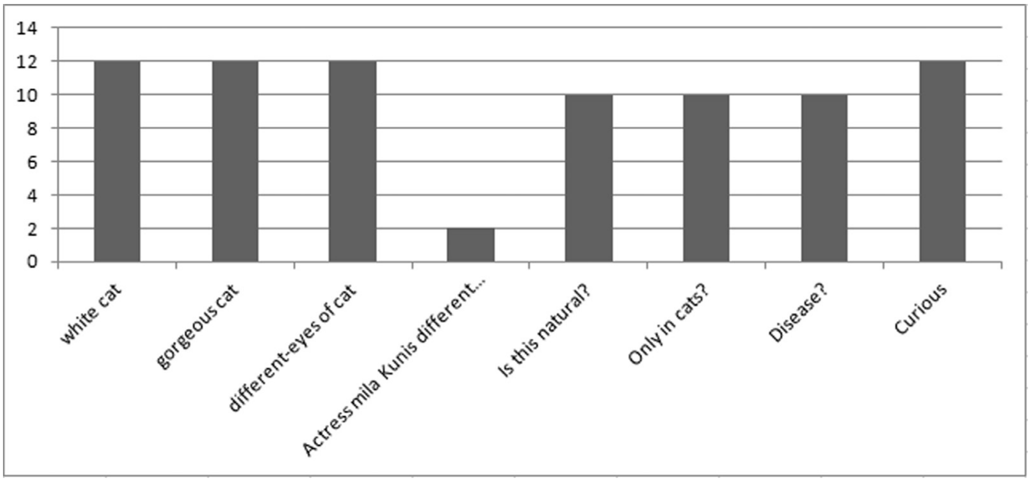


Fig. 12. Human-subject responses to Fig. 11.

deployment and modulation, processes of manipulation and stitching of multisensory memories into seamless perception of the real-world, a probable generic format of multimodal information-representation (this point stems from the observation of the innate arousal of emotional stirrings through instrumental music), the activation of volition. The model however attempts at providing a premise for constructive 'thinking on thinking'.

(c) Representation of meanings, through assimilation of multimodal qualia derived from experiences and commonsense, and the role of the self are major features of the design.
(d) The interdependence between objective knowledge, subjective experiences and choice (arising out of interest or importance) in bespoke comprehension of the real-world form the foundations of the proposition.
(e) Through inclusion of subjective parameters in the formulations, the model has tried to provide a basis for the identification of emotions in stimulus from peers and the consequent arousal of empathy.
(f) The model traverses from the macrocosm of the context to the microcosm of innate responses and back, towards coverage of all the different levels of cognition [28,29] and thinking [22] for real-world understanding. It considers

hardwired instinctive reactions, as well as learned reactions that turn into instinctive reaction with gradual reinforcement, and includes scope for creative/metaphorical thinking.

(g) Consideration of *time* in the formulations is a significant design strategy. This parameter is crucial in the emulation of the 'unified self [38]' and the 'experiencing self [22]'
(h) A preliminary mechanism for dealing with novel words and abstract concepts has been incorporated.
(i) The design is founded on the system's ability to generate natural language mentalese for information in any modality. An ideal framework would be one where the system can directly operate on multimodal information e.g., internally visualize colour-blending, image-superimposition or sound-composition.
(j) The model is an attempt at contributing to the realization of artificial 'general' intelligence, thus envisioning application in i) human-machine coordination where both verbal and non-verbal multimodal cues require being considered for effective interaction, and ii) as a basis of multimodal deep-learning frameworks for comprehension of complex real-world environments.

Aiming at synthesis of the proposed model, the task that follows hereon is the design of data structures (a preliminary outline of which can be found in Fig. 7) that would encourage the a) encapsulation of innate-response-annotated multisensory information in the long-term and working memory of the system, and b) permit interactions between them in the form of Z*-numbers. It is in this area that our research is currently directed.

5. Conclusion

The work described in this article stems from our investigations on the factors leading to the endogenous instantiation of thoughts in a 'social [45]' cognitive system during real-world comprehension. Envisioning the Z*-numbers [4,6] as abstractions of meanings of thoughts expressed as natural language mentalese, the conceptualized framework attempts emulation of all the layers of contemplation [28,29] - from instinctive reactions to self-conscious emotions and empathy, and 'slow and fast thinking [22]' . The algorithm elucidates macro-steps of contemplation and comprehension, and is inspired by brain-processes.

Our design demonstrates a conscious shift away from a unimodal, objective perspective of real-world comprehension. It deals with atomic elements of multisensory environmental stimuli, arousal of innate and complex emotions, interactions between the objective and subjective components of experiences and commonsense, formation of novel concepts, consciousness, qualia, curiosity and surprise, interest and relevance, autogenous and volitional attention distribution across a region of interest, and the context towards formalizations for bespoke perception and behaviour. Results of theoretical-runs through the design have been validated against responses of human subjects. We intend to test the algorithm across diverse input-modalities, complex scenarios and correspondences against human thoughts. An investigation of the applicability of the algorithm across machine-mind cognitive frameworks is a future research problem.

The model is yet in its early design-stages and is envisaged to evolve as we gain insights into the fundamentals of the working of the human mind. Synthesis of the framework calls for formulation of Z*-number operators that emulate representation and processes of thoughts in action, mechanisms for seamless integration of intra-object modalities across space and time, machine-mind memory-management processes, and design of data-structures that would support the representation and manipulation of such data. Technology gaps – in the nature of multisensory neuronal equivalents for feedforward [13] traces through base architectural components for robust real-world information handling – need to be addressed as well. We are currently working on the formalization of working-memory structures to support execution of the proposed multisensory, data-driven algorithm for a real-world comprehending cognitive system. The ideas herein aim to contribute to autonomous mind-development initiatives for man-machine symbiosis.

"*You end up with tremendous respect for a human being if you' re a roboticist*" - Joseph Engelberger, 1985

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References

[1] R.A. Aliev, O.H. Huseynov, R.R. Aliyev, A.A. Alizadeh, *The Arithmetic of Z-Numbers*, World Scientific Publishing Co, NJ, USA, 2015.
[2] V. Arstila, D. Lloyd (Eds.), Subjective Time: The Philosophy, Psychology and Neuroscience of Temporality, MIT Press, MA, USA, 2014.
[3] D. Balduzzi, G. Tononi, Qualia: The geometry of integrated information, *PLoS Computational. Biology*. 5 (2009) e1000462.
[4] R. Banerjee, S.K. Pal, Z*-numbers: Augmented Z-numbers for machine-subjectivity representation, Inf. Sci. 323 (2015) 143–178.
[5] R. Banerjee, S.K. Pal, Text comprehension and the computational mind-agencies, in: Natural Computing, 14, Springer, 2015, pp. 603–635.
[6] R. Banerjee, S.K. Pal, A machine-mind architecture and Z*-numbers for real-world comprehension, in: A. Pal, S.K. Pal (Eds.), Pattern Recognition and Big Data, World Scientific, Singapore, 2017, pp. 807–844.
[7] L.W. Barsalou, Perceptual symbol systems, Behav. Brain Sci. 22 (1999) 577–660.
[8] C.O. Callaghan, Grades of multisensory awareness, Mind Lang. 32 (2017) 155–181.
[9] A. Chatterjee, Disembodying cognition, Lang. Cognition 2 (2010) 79–116.
[10] A. Damasio, *Self Comes to Mind: Constructing the Conscious Brain*, Vintage Books, London, UK, 2012.

[11] W. Duch, R. Oentaryo, M. Pasquier, Cognitive Architectures: Where do we go from here?, in: P. Wang, B. Goertzel, S. Franklin (Eds.) Frontiers in Artificial Intelligence and Applications, IOS Press, Amsterdam, NL, 2008, pp. 122–136.
[12] P. Ekman, in: T. Dalgleish, M. Power (Eds.), *Handbook of Cognition and Emotion*, John Wiley and Sons, Ltd, Sussex, UK, 1999, pp. 45–60.
[13] J.J. Foxe, C.E. Schroeder, The case for feedforward multisensory convergence during early cortical processing, Neuroreport 16 (2005) 419–423.
[14] S. Franklin, IDA: A conscious artifact? J. Consciousness Stud. 10 (2003) 47–66.
[15] S. Franklin, T. Madl, S. D'Mello, J. Snaider, LIDA: A systems-level architecture for cognition, emotion, and learning, IEEE Trans. Auton. Mental Dev. 6 (2014) 19–41.
[16] J. Gottlieb, P.-Y. Oudeyer, M. Lopes, A. Baranes, Information-seeking, curiosity, and attention: computational and neural mechanisms, Trends Cognit. Sci. 17 (2013) 585–593.
[17] T.A. Harley, *The Psychology of Language: From Data to Theory*, Psychology Press - Taylor and Francis Group, NY, USA, 2008.
[18] C.L.M. Hill, J.A. Updegraff, Mindfulness and its relationship to emotional regulation, Emotion 12 (2012) 81–90.
[19] D. Hofstadter, Analogy as the core of cognition, in: D. Gentner, K.J. Holyoak, B.N. Kokinov (Eds.), The Analogical Mind: Perspectives from Cognitive Science, MIT Press, MA, USA, 2001, pp. 499–538.
[20] N.P. Holmes, C. Spence, Multisensory integration: Space, time and superadditivity, Curr. Biol. 15 (2005) 762–764.
[21] W. Jarrold, P.Z. Yeh, The social-emotional Turing challenge, in: *AI Magazine: Beyond the Turing Test*, 2016, pp. 31–38.
[22] D. Kahneman, *Thinking, Fast and Slow*, Farrar, Straus and Giroux, NY, USA, 2011.
[23] T.C. Kietzmann, P. König, Effects of contextual information and stimulus ambiguity on overt visual sampling behavior, Vision Res. 110 (2015) 76–86.
[24] J.F. Kihlstrom, *The Person–Situation Interaction*, Oxford University Press, NY, USA, 2013.
[25] L. McCauley, S. Franklin, M. Bogner, An emotion-based "conscious" software agent architecture, in: A. Paiva (Ed.), Affective Interactions, Springer-Verlag, Berlin, Heidelberg, 2000, pp. 107–120.
[26] B. Mcmurray, Language at three timescales: The role of real-time processes in language development and evolution, Top. Cognit. Sci. 8 (2016) 393–407.
[27] A.B. Miller, *Einstein, Picasso: Space, Time and the Beauty That Causes Havoc*, Basic Books, NY, USA, 2002.
[28] M. Minsky, *The Society of Mind*, Simon & Schuster Inc., NY, USA, 1986.
[29] M.L. Minsky, *The Emotion Machine: Commonsense Thinking, Artificial Intelligence, and the Future of the Human Mind*, Simon and Schuster, Inc., NY, USA, 2006.
[30] T. Mitchell, W. Cohen, E. Hruschka, P. Talukdar, J. Betteridge, A. Carlson, B. Dalvi, M. Gardner, B. Kisiel, J. Krishnamurthy, N. Lao, K. Mazaitis, T. Mohamed, N. Nakashole, E. Platanios, A. Ritter, M. Samadi, B. Settles, R. Wang, D. Wijaya, A. Gupta, X. Chen, A. Saparov, M. Greaves, J. Welling, Never-ending learning, in: Proc. 29th AAAI Conference on Aritificial Intelligence, AAAI Press, CA, USA, 2015.
[31] D.S. Modha, R. Ananthanarayanan, S.K. Esser, A. Ndirango, A.J. Sherbondy, R. Singh, Cognitive computing, Commun. ACM 54 (2011) 62–71.
[32] D.A. Norman, Toward a theory of memory and attention, Psychol. Rev. 75 (1968) 522–536.
[33] P.-Y. Oudeyer, L.B. Smith, How evolution may work through curiosity-driven developmental process, Top. Cognit. Sci. 8 (2016) 492–502.
[34] S.K. Pal, R. Banerjee, S. Dutta, S. Sen Sarma, An insight into the Z-number approach to CWW, Fundamenta Informaticae 124 (2013) 197–229.
[35] H. Peng, J. Wang, Hesitant uncertain linguistic Z-numbers and their application in multi-criteria group decision-making problems, Int. J. Fuzzy Syst. (2016) 1–16.
[36] R.A. Peters, K.A. Hambuchen, R.E. Bodenheimer, The sensory ego-sphere: A mediating interface between sensors and cognition, Auton. Robots 26 (2009) 1–19.
[37] S. Pinker, *The Stuff of Thought: Language as a Window into Human Nature*, Penguin Books (Viking Press), NY, USA, 2007.
[38] V.S. Ramachandran, *The Tell-Tale Brain: A Neuroscientist's Quest for What Makes Us Human*, W.W. Norton and Company, NY, USA, 2010.
[39] W. Schneider, R.M. Shiffrin, Controlled and automatic human information processing: I. detection, search and attention, Psychol. Rev. 84 (1977) 1–66.
[40] J.M. Schwartz, S. Begley, *The Mind and the Brain: Neuroplasticity and the Power of Mental Force*, Harper Collins, NY, USA, 2002.
[41] N. Srivastava, E. Vul, Attention dynamics in multiple object tracking, in: D.C. Noelle, R. Dale, A.S. Warlaumont, J. Yoshimi, T. Matlock, C.D. Jennings (Eds.), Proc. 37th Annual Meeting of the Cognitive Science Society, Cognitive Science Society, TX, USA, 2015, pp. 2266–2271.
[42] P. Taylor, J.N. Hobbs, J. Burroni, H.T.T. Siegelmann, The global landscape of cognition: Hierarchical aggregation as an organizational principle of human cortical networks and functions, Scientific Reports, Nature 5 (2015) 1–18.
[43] A.M. Treisman, G. Gelade, A feature-integration theory of attention, Cognit. Psychol. 12 (1980) 97–136.
[44] E. Tulving, Memory and consciousness, Can. Psychol./Psychologie Canadienne 26 (1985) 1–12.
[45] J. Wiles, Will social robots need to be consciously aware? (in the newsletter of the autonomous mental development technical committee), IEEE Trans. Auton. Mental Dev. 11 (2014) 14–15.
[46] L.A. Zadeh, A note on Z-numbers, Inf. Sci. 181 (2011) 2923–2932.