Research Article

The Emergence of Consciousness in a Physical Universe

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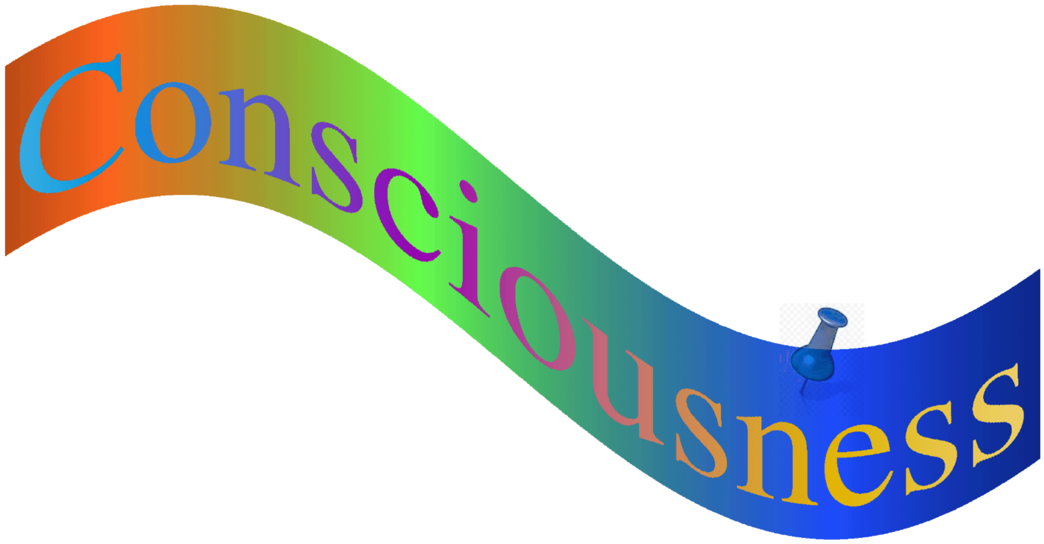
Consciousness appears so mysterious and hard to formulate within the physical sciences because present-day scientific thinking excludes an element of reality and a general mechanics of its processing from its consideration. The primary missing element is the reality of information in the physical universe as an intrinsic causal correlate of observable physical states. Moreover, there exists a general formalism of information processing that is universally applicable to the processing resulting from each physical interaction. As shown, the formalism further enables a general mechanism to construct arbitrary structured and abstract semantics or object descriptions in modular hierarchy, as well as a powerful mechanism of population coding to represent arbitrary precision and variation in object description, resolving the combinatorial problem. Here, a semantic value, or simply semantics, is equivalent (≡) to the content of information of causal correlation, and is treated as a value to enable its formal processing. The primary motive here is to lay down a formal account of information (semantic) processing that leads to bridging the conceptual gap between the objectively observable elements in nature and subjective consciousness. It is shown that the qualities we associate with consciousness are causally correlated semantics of relation that a represented agency holds with other objects within a dynamically evolving semantic structure, where the state of the population of physical systems (neurons) correlating with the structure holds causal powers to effect appropriate behavior. Since the information (semantic value) arises from natural causal dependence, the correlation-based consciousness forms an undeniable reality of existence. It is derived here how a semantic value equivalent to 'a self as an observer of objects and controller of actions' is constructed. If the semantic components of a conscious experience, such as the self, the objects of experience, and the relation of experience attributing the self as the owner or experiencer, causally correlate with a system's state having causal influence in action, then it suffices to bridge the gap between objective reality and subjective consciousness. That is, the semantic value corresponding to the thoughts and senses is the reality of nature the semantics of self relates to as the owner. Moreover, the semantics of 'self as an observer and controller of action' is itself shown to form a part of observed objects, giving rise to self-awareness.



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1. Introduction and definitions

The phenomenon of consciousness is the most apparent reality of nature to us all as humans. It must, therefore, be explicable and expressible in terms of the objective function in nature. No description of nature can be said to be comprehensive if it does not lead to the understanding of consciousness. Since we aim to bridge the gap between the objective function and the subjective consciousness, it is imperative that this work clearly establishes the interpreter-independent reality of information, lays down the mechanics of processing that is testable on artificial devices and observable in the brain, quantifies the mechanics of integration and abstraction, derives the emergence of semantics of an agency that satisfies the criterion of, or qualifies to, being a conscious agent, resolves contentious problems in the domains of information and consciousness, and makes testable predictions. Since this work is based on the undeniable objective causal function of elements in nature, even the subjectivity is shown to have an objective basis. Causal function refers to the function of an object or a state, physical or representational, to effect a regular change within limits, in the respective domains, by which the object or the state is identifiable. Unless specified otherwise, in this work, the term 'representation' exclusively refers to the causal correlation of a coherent physical state without any symbolism.

The idea and the plan: The basic idea here is that the qualities we associate with consciousness are the semantics of relation that a represented agency holds with the represented objects. Stated differently, within a structured or integrated semantics, the relation that one specific object bears with other objects has the qualities that we have come to refer to as consciousness. The plan: 1. The reality of information is shown to

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arise from the regularity of causal function in nature. Information necessarily expresses or qualifies objects in terms of implicit or explicit relation. The content of information is treated as a value enabling a general formalism for its processing. 2. Given the same regularity of causal function, an interaction is definable as mutually inter-dependent, hence bounded, transitions in the state of physical entities (systems). This perspective allows a generic expression to be constructed to formally evaluate the causal dependence (correlate) of a resultant state of a system on precursor states of interacting systems. 3. This generic expression is then shown to be potent to express all relations, including temporal and causal relations, enabling such relations to be represented by a state as its correlate. 4. The same generic expression also enables a mechanism of population coding that allows a relation to be represented with arbitrary variations and precision without requiring mathematical consistency. 5. The mechanism of representing arbitrary relations is then shown to capture structured and abstract semantics of complex systems and their functions. Abstraction is defined as the formation of a class from the instances and from functional relations, which serves as a semantic space. 6. A simplified example of echolocation is then worked out to show how the active state of an agent in a network of inter-dependence can represent the relative placement of an observing system itself with respect to other systems in the field of view, which forms a component of self. 7. The ability to represent causal relations further allows a systematic integration of semantics in modular hierarchy that expresses a class of structural configurations and dynamic functions of an evolved system or organism. The referable semantics of the structured class as a unified system is then shown to possess several characteristics of self. 8. Evolution based on selection creates a system with causal function towards survival. A processing system like the brain may 'then evolve' to represent the dynamics and the causal function of the unified system. It is shown how the integration of the structured semantics of 'a unified system with abilities of observing, referencing, acting, and controlling the actions' takes place. It is then inferred how the semantics of the function of the unified system (self) posits it as the bearer of the properties we identify with consciousness. 9. The process is then extended to include how the referential and causal relations of the represented self with the objects form a part of observable objects, leading to a semantic structure of self-conscious agency. 10. Lastly, the conclusion section is especially devoted to discussing and presenting a resolution to several known problems relating to consciousness. A subsection is especially included to enlist predictions that are testable via implementation on artificial devices and observable in the brain.

Our understanding of consciousness today lacks any relation it may have with the third-person observable causal function in nature. Therefore, they appear as different in category or as independent elements of reality. On a subjective experiential level, consciousness forms the basis of all perceptions, senses, knowledge, memories, interpretative and modeling abilities, and the rationale of decision-making and action. In fact, the very perception of the undeniable reality of 'self as a conscious agency' is also based on the same consciousness, as Descartes observed. Yet, inter-personal objective access to the same conscious perceptions remains impossible, making an objective account difficult.

As we look around, we observe objects and their inter-relations embedded in $4.\pi$ steradian (sr) space; consider relations and processes as objects, for they are referable. We especially note that the perceived features of objects, see Fig.1, are constructed of semantic values.

Figure 1. The observed features of objects, such as shape, size, color, and relative placement, are undeniably apparent semantics; therefore, they must be constructible and referable by natural processes.

For instance, the semantic value associated with a book or a ball in the field of view is constructed of shape, size, polygonal surfaces, roundness, color, texture, placement relative to other objects, regular array of leaves, etc. We are concerned here with semantics, not with their conscious perception. We further notice the apparent realism of the semantics of information; it is undeniable, concrete, and non-probabilistic regardless of the external reality of the book and the ball. For instance, can we deny the knowledge of the semantics of the rectangular shape of the book and the roundness of the ball? Moreover, do we require any language, symbolism, or interpretation to know it? As per the norm in science, we must accept this observed reality as part of the natural universe and seek to establish its foundational basis. One may draw an immediate inference that all elements of consciousness, including the self and its relation with objects we call perception, are constructed of such semantic values, as shown here. Since information does not interact physically, yet is undeniably apparent, it must have a non-falsifiable existence in reality. That is, the causal function in nature must be directly responsible for this reality. The categorically different reality of information[1][2] is not constructible from physically measurable entities in nature. Overriding different senses in which the term 'information' is used in natural sciences[3][4], here, it is used to refer to what it expresses, the semantic value content.

1.1. Grounding of information as an element of reality

In its endeavor to build a physical model of natural phenomena, humanity has ignored certain elements of natural processes that relate physically observable elements to subjective reality. Three fundamental paradigms are identified as missing in our present-day model of the natural world that are critical for our understanding of the emergence of consciousness. The first missing element is the basis of information in the constancy of causal function[1]. The physical universe, as observed from within, undergoes change. The changes follow certain uniformity and regularity (constancy), such that an observable state, S, of a physical system, P, bears a dependence on certain other states $\{S_x\}$ within specific limits, where $\{S_x\}$ may include relative static or dynamic quantities (space, time, rates of change, etc.) in conjunction and / or disjunction. That is, if $\{S_x\}$ were not to form a part of contextual reality within the limits, the state S of P could not have an existential reality either. Therefore, S of P intrinsically and causally must correlate with the semantic specification of $\{S_x\}$. It is noteworthy that an individual element of $\{S_x\}$ is not said to cause S of P, but rather S of P causally depends on specific conjunctions of elements in $\{S_x\}$. This relation of the 'present to the precursor' or 'posterior to the prior' is referred to here as 'natural causal dependence'. It is referred to as 'natural' to imply the independence of this relation from any model or interpretation to mean what really exists, an ontological connotation.

For instance, the 'mass state' of a physical system Q is a relatable quality, for it determines Q's causal function in an interaction and is a basis of Q's relation with other objects. Hence, the information of the 'mass state' of Q forms a primitive of semantic value, a meaningful object grounded in reality without a qualifying label. An interacting system P responds to the relative measure of this quality, which reflects in a relative transition in P's state, such as the angle of deflection as marked by two arrows in Fig.2. Similarly, the information of the spatial placement of Q relative to P is a semantic value of consequence to P. As P undergoes a transition in its trajectory due to the causal function of mass M and the relative placement R of Q, as shown in Fig.2, the resultant state S of P must 'correlate with' (symbol $\Rightarrow$) the semantic values of the specification of mass and relative placement of Q, symbolically denoted as follows.

$$S_P \Rightarrow (M, R)_Q \tag{1}$$

Since this correlation arises from natural causal function, it must include whatever reality, fundamental or emergent, the semantics of the qualities of mass and spatial placement entail and their measures.

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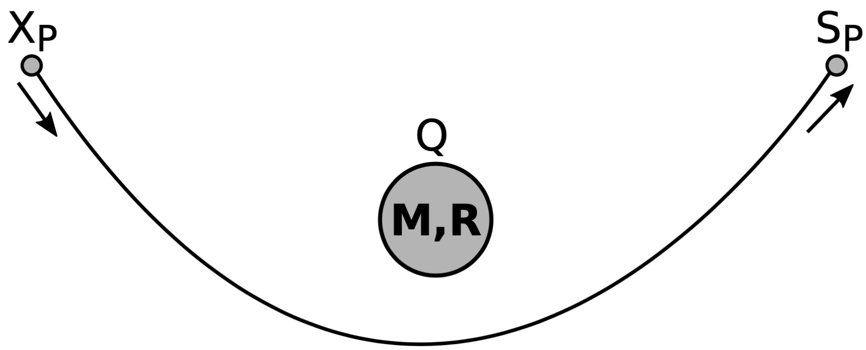

Figure 2. In an interaction with system Q, P transitions into state S, designated as S_P. S_P is then said to correlate with precursor causal states of interacting systems, including its own prior state X_P.

A qualitative character can be thought of as an abstraction of a class or parametric space. The value on the RHS includes a positive correlation with causally permissible limits of (M,R) in reality and a negative correlation with the rest of the space, as briefed below. Here, R denotes a composite of the temporal relation of Q's placement to P. While a positive correlation indicates a possible range of values or configurations for precursor states in reality that may result in S_P, a negative correlation indicates forbidden values for precursor states[1]. This is how the semantic values are grounded in the causal function as covered by the laws advanced in[1] and summarized below.

On semantics: The term semantics is often associated with the study of meaning, or just the meaning; it is also used in literature in the contexts of semantic information, semantic memory, semantic knowledge, semantic processing, and semantic categories [1]. In this work, it is used to designate the value or content of information that arises as a causal correlate of a physical state. It is shown here how the semantic values forming thoughts and perceptions emerge as the causal correlate of neural states. Hence, the term semantic value as a reference to the content of information is rather accurate. One must ask, what is it that a physical state causally correlates with that entails the quality and quantity of states and relations in nature? Yet, if a reader finds this notion of 'semantics' troublesome to reconcile, one may replace it with a new term 'semcorr' for 'Semantic Value of Correlation' (SVC) to designate the quality of the causal correlate.

S_P is said to correlate with or represent the semantic value, but this representation is neither symbolic nor artificially assigned. It is a direct and intrinsic association of a state with the value not accessible to a third-person observation. Although a projection of intrinsic correlation is analyzable within the limits of constraints

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of causal dependence and the initial conditions, as is the case while analyzing the result of an experiment. The transformed state of P, S_P, has a causal influence that conforms to this correlation.

The second missing element is a generic formalism[1] to express universally all relations, which also captures the causal dependence of an observable resultant state on the precursor states of interacting systems. The formalism quantifies information processing resulting from an interaction; the resultant value constitutes an intrinsic correlate of the resultant state. It is remarkable to note that the same expression also serves as a generic constructor of all semantics, structured and abstract, as shown in[1] and briefed here. Moreover, the expression also leads to the population coding system, as shown below and as computationally simulated in[1].

The third missing element is a conceptual framework for the self to be a part of a structured semantics, like any other objects the self is said to be conscious of. That is, it is the represented semantics of a relation that expresses the self as an observer of objects and a controller of actions. Moreover, by virtue of being a causal correlate of a state, the semantic value is correlatable with the representable semantics of the consequence of the state. Therefore, the problem of constructing the description of consciousness reduces to the problem of representing the semantics of the self and its relation to the objects of experience. The critical components of the semantics of the self are 'self as an embodiment of the carrying system', 'self as an observer', 'self as an actor', 'self as the owner of senses', and 'self as a controller of action / behavior'. For the purpose of constructing a causal description of consciousness, the development here is based on causal function in nature without a dependence on a specific system like the brain, even though the examples are picked from it.

Since we aim to construct a semantic representation of all that is referable, we need a generic term for such a reference. In this text, the term 'object' is used as a universal reference to all, including elements of physical reality, relations and expressions, temporal events and processes, discrete and analog values, and symbolic references – elemental, structured, or abstract. An abstract object exclusively refers to the semantics expressed by a disjunctive relation among objects or instances that form a class. For instance, a disjunction of instances of 'right angle' is an abstract object referable as a class. In fact, referability arises for an object only when a semantic value is constructed within the domain of representation. A language also emerges from such referability (Section.8.4 of[1]). Withstanding the limitations of linguistic expressions, unless a reference is created via a causal correlate, no object is referable. It may be noted that with every interaction, a reference is created via a causal correlate. Hence, all elements of our thoughts and experiences, as well as linguistic expressions, are represented objects (semantics) without exception; this is also apparent from this development. Since an object has a description as a structural relation among its components and a functional relation with other objects within a system or a frame of reference, it is always expressed only via relation among objects. Therefore, an object description or definition is equivalent to the semantics of relation among objects. When referring to identity, we use the term ‘object’, and when referring to the quality of description, we use the term ‘semantics’.

1.2. A definition of consciousness

The mystery surrounding consciousness only intensifies with time. The number of proposals to deal with it grows so rapidly that it has become difficult to summarize them within the scope and limitations of this article. An uninitiated reader may begin with[5][6][7]. A reader may refer to some of the reviews of common and important variants on this topic – Butlin et.al.: Consciousness in Artificial Intelligence[8]; Sattin et.al.: Theoretical Models of Consciousness[9]; Francken et.al.: An academic survey on theoretical foundations[10]; Ned Block: Comparing the major theories[11]; Uriah Kriegel: Theories of consciousness and self-representational approaches[12][13]; Melanie Boly: Consciousness in humans and non-human animals: recent advances and future directions[14]; Sun and Franklin: Computational models of consciousness[15].

The work presented here differs from all others in a few critical ways. First, no causal or non-causal hypothesis is proposed here to connect consciousness directly to the physical world. Instead, it is shown to emerge from semantic values grounded in natural causal function; it may be referred to as Emergence of Consciousness from Causal Information (ECCI, pronounced ‘ekki’ as per the first syllable of the terms). Second, a formal mechanism of semantic processing is presented, which is directly applicable to neural systems and implementable on artificial devices. Third, a principle based on the constancy of relations is introduced as a uniform mechanism to construct object descriptions via structural and functional relations. Fourth, a mechanism of population coding of semantic values is laid down quantitatively, which is testable on artificial devices and observable in neural systems. For a deeper comparison with a few noted models, one may refer to Supplement-1.

A functional definition of consciousness: Consciousness refers to a dynamic structured relation R that an object U holds with other objects within a causally constructed semantic structure S, where R includes a referential relation (reference) to the objects and a causal relation to effect specific change to the referent. A referential relation designates U as the bearer of the ability to refer to an object, and a causal relation as the ability to effect a change to an object. All of this is shown to be contained in the constructed semantic structure S. Clearly, the relation R defines the object U as the observer of objects and the agency of specific change. Here, an object is a semantic value having a temporal dimension or a dynamic character. The relation R is stated to be dynamic even if certain specifics may not change during a reference, for no static relation bears an intrinsic property to change, and for the referential and causal relations remain undefined for static contexts. A change to the referent includes both a change in the perspective of U or to the objects; in either case, the referent semantics undergoes a change. In every perception of thoughts and senses, it is the object U that relates to other objects of perception, where the thoughts and senses constitute the structured semantics S. That is, the seer, the seen, and the act of seeing, or the perceiver and the perception, are parts of a uniformly constructed semantic structure with causal consequence. What is explicit in this definition is that the phenomenon of consciousness has no existence out of such semantic structures. Instantiating a causal relation (action) affects the objects represented, where the signals in the physical substrate are transported to effect internal or external change, which in turn can be observed for conformance. In this work, we aim to lay down the construction of the semantic structure of referential and causal relations to the referent objects.

This definition is minimal, primary, or first order, which only requires a constitution of an observing self without self-referentiality, relating to other objects resulting in causal control of action. A stronger or second order definition includes the relation R that the object U holds with other objects as a part of referable objects relating to a new U, U-new. This makes it possible to refer to 'an observing and controlling self, U'. The controller element is necessary from the evolutionary perspective as discussed in Section.4.4. The second order definition permits the construction and reporting of semantics like, "I am conscious of X", "I experience X", and "I effected the change X".

2. The mechanics of information processing

In order to construct an information-based emergence of consciousness, we take the following steps. First, information is established as an interpreter-independent reality from the causal function of the physical universe. Second, a general expression E is advanced to quantify the information processing at each physical interaction organizable in modular hierarchy to represent higher order structured semantics. Third, this expression is shown to be general enough to express all semantics, structured and abstract. Fourth, an implementable uniform principle is formulated to construct descriptions of all objects, including relations and processes. Fifth, a population coding mechanism[16][17][18] is derived from E to express combinatorially unlimited variation in object description. These principles and formalisms are also presented in[1] from a different standpoint. For self-sufficiency, the relevant points are presented below.

1. As stated above, an observable resultant state intrinsically correlates with the specification of precursor states with limits of positive and negative correlation. The following law quantifies the semantic correlation as presented first in [1] and demonstrated with a computer simulation. This is amenable to empirical verification via observation of neural function and organization. One may consider this as a hypothesis, but it is also self-evident and comprehensive.

   The law: Post-interaction, an observable resultant state S of a physical system P correlates with a definite semantic value C that is derived from all causally equivalent configurations of reality, specifiable in terms of values of precursor states of interacting systems, that result in the state S of P. The components of

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semantic value C are given by the following expressions:

(i) disjunction of conjunctions of values of respective states in each configuration;

(ii) disjunction of conjunctions of semantic values of correlation, from arbitrary spaces of mutual relevance, of respective states in each configuration within the constraints of Rule.(i).

We may observe that the law depends on the transition of states, for that is what is observable in a measurement, not the underlying law or the relation, which may form a part of correlation. Let A and O designate infix binary operators for conjunction and disjunction respectively, with A having a higher precedence. Since each of the operators is commutative, no specific ordering is required for their respective operands. For higher precedence of A , parentheses on the RHS in Eqn.2 are redundant.

$$S_P \Rightarrow (v_1^1\ A\ v_2^1\ A\ v_3^1\ A \ldots)\ O\ (v_1^2\ A\ v_2^2\ A\ v_3^2\ A \ldots)\ O \ldots \tag{2}$$

Here, the LHS specifies a state S of P and the RHS its causal correlation; v_j^i specifies j^{th} value in conjunction of i^{th} term in disjunction. v_j^i is an arbitrary semantic value specified with positive and negative limits, which could be a state value itself as per (i), or a value of its correlation as per (ii) above. This causal correlation is transparent to classical or quantum consideration (see Section 2.3 in[1]), for it depends on observable states alone. In general, the LHS may have an expression like the RHS, a disjunction of conjunctions of arbitrary state values, in which case, the RHS replicates the same expression but with each state value substituted by its correlation, as expressed on the RHS. For instance, in the neural system, a neuron is activated by the active states of (signals from) multiple projecting neurons, each having its own correlation profile as given by the RHS. Fig.3 illustrates the mechanism of quantitative evaluation as used in a computer simulation in[1].

Rule.(ii) inductively takes care of continued causal dependence. With the limits of correlation in (i), (ii) extends the correlation to other parametric spaces of relevance under the limits of causal dependence, which includes the extended space and time to the past and the future. For instance, when a ray of light activates a neuron in the retina, the active state not only correlates with the conjunction of the state of photons in the ray as per (i), but further correlates with the relevant causal context or constraints of the ray of light as per (ii), which includes positive correlation with a narrow range of the angle of incidence and negative correlation with the rest of the space with respect to the ocular system. Active states of neighboring neurons similarly correlate with overlapping values of angles of incidence in a neighborhood, making the space of angles mutually relevant. What is important to note here is that no component of the neural system or organization is required to encode, decode, or interpret in any way what a neural state correlates with or represents; the activation pattern of neurons in the retina holds the same relation that the rays of light activating them hold, which in turn correlates with the characteristic features in the visual field. Rule.(ii) plays a critical role in constructing higher-order structured and abstract semantics.

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Since this constitutes a paradigm shift from the present-day consideration of information, a reader is advised to take special note of its foundational basis to follow the discussion and derivation laid down here. In fact, the causal basis of information is tested every time the result of an experiment in the physical sciences is interpreted with presumed laws of causal dependence.

2. In this work, conjunction and disjunction are not logical operators to accept True or False as their operands referring to arbitrary propositions. These binary operators accept three values of correlation, Positive (Pos), Negative (Neg), and Null (Nul), as operands that refer to positive, negative, and null correlation with limits of semantic values – relative limits of causal state description (Fig.2) are an instance of such values. In fact, a binary representation of {Pos, Neg, Nul} as {01, 00, 11} maps conjunction and disjunction to binary operations of AND and inclusive OR respectively. The set of values {Pos, Neg, Nul} together with conjunction and disjunction operators forms a mathematical structure, a new kind of comprehensive mechanism of information processing as detailed in Section.3.1 of [1] and presented here in Table.1 and Fig.3.

Corr1	Corr2	Conjunction	Disjunction
01 (Pos)	01 (Pos)	01 (Pos)	01 (Pos)
01 (Pos)	00 (Neg)	00 (Neg)	01 (Pos)
01 (Pos)	11 (Nul)	01 (Pos)	11 (Nul)
00 (Neg)	00 (Neg)	00 (Neg)	00 (Neg)
00 (Neg)	11 (Nul)	00 (Neg)	11 (Nul)
11 (Nul)	11 (Nul)	11 (Nul)	11 (Nul)

Table 1. The table specifies the result of conjunction and disjunction on correlation values.

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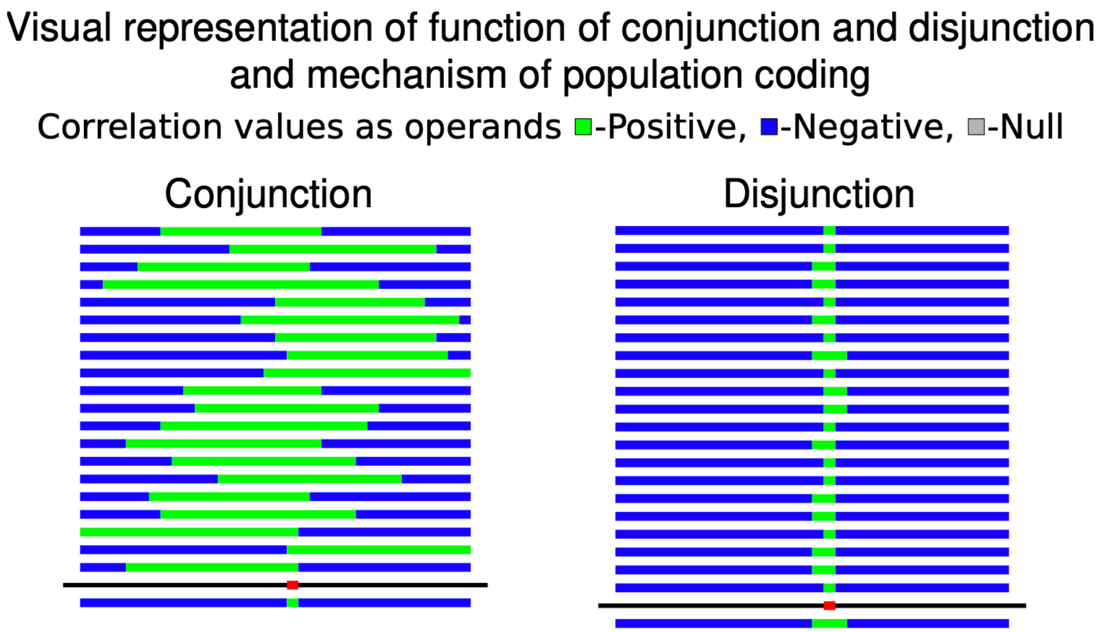

Figure 3. A graphical illustration of methods of conjunction and disjunction, and the mechanism of population coding. Each horizontal color bar under conjunction represents a correlation profile of an active agent (say a neuron) in an arbitrary space of semantics as per the causal correlation (Green: Positive, Blue: Negative). For example, an active state of a neuron may correlate positively with a range of orientation of a line segment, and negatively with the rest of the space. The actual data for the figure is taken from a simulation presented in Section.7 of [1] by the same author. Each bar represents the same range of space; a negative correlation is implied for the rest of the space. The result of conjunction on columns of values is displayed below the black line, which shows a sharp positive correlation as a result of conjunction, where the red mark on each black line shows the instance of the actual orientation value presented for simulation. Therefore, when a set of these agents together activate another agent, the active state of the recipient agent represents the value below the black line. If the recipient agent can be activated by subsets of input signals, then its state correlates with the disjunction of conjunctions in specific subsets as shown on the right. The correlation profile may vary dynamically in a re-entrant system. The salient properties of population coding in representing arbitrary variations, higher precision, robustness, and in graceful degradation at the loss of individual agents are apparent and noteworthy. It is instructive to consider the color bars as representing the angle between two lines, resulting in a sharp angular relation as a result of conjunction among a population. The mechanism remains consistent even when each column of the width of the red mark on the color bars is taken from different semantic spaces, or when the bar represents a continuous range in a space.

2. A conjunction of semantic values evaluates to greater specificity with narrower positive correlation when the values overlap in an object space, or to a specific composition when the values come from non-

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overlapping spaces. For instance, a line segment is specifiable by a conjunction of extents of overlapping points or pixels. The resultant value functionally further correlates with specific limits of length, width, and orientation, extending the mutually relevant parametric spaces. Disjunction functions as a mechanism of generalization, giving rise to abstract semantics of a class, relation, or structure [1], e.g., semantics of 'right angle' from instances of right angle as shown in Fig.4. A class object encapsulates a relation that holds on the instances (members) of the class as presented in [1]. Hence, the disjunction causes the emergence of an irreducible abstract semantics, making available a reference to a class object without referring to an instance. This abstraction, arising from a limited range of observed instances, cannot be a part of a consistent, formal mathematical system[1]. But it can be included as a rule or an axiom and interpreted by a system with abilities to represent a class via disjunction, which may even hold for all possible instances, such as a+b=b+a for numbers. Now, since all objects and expressions are constructed of objects, including inter-relations, the method of conjunction to capture a composition and the method of disjunction to represent the class of structure together form a comprehensive mechanism to construct semantics of all objects[1]. The mechanism is suitable for implementation by evolving biological systems via population coding (See Fig.3).

3. Evidently, the mechanism of information processing, as laid down above, directly corresponds to neural function and their re-entrant network in modular hierarchy. Neurons in the brain process information via a coherence-building mechanism based on temporal synchronization that directly maps to the function of conjunction and disjunction. A neuron turns active when a number of synchronized (closely spaced) action potentials (APs) are received at its input ports (dendrites / soma) that cross the activation threshold, where the threshold may be reached even by subsets of input signals. Therefore, the active state of a neuron at the moment of activation qualifies to represent the semantics of a disjunction of conjunctions of semantic values resulting from each subset of APs of the presynaptic active neurons. As shown below, a disjunction of such subsets allows a system a flexibility to require sufficiency of the limit of conjunction via active inhibition in a re-entrant network to select the appropriate level of specificity and abstraction. The fundamental mechanism of representation and processing of the semantics of information is thus established.
4. A point to note here is that an observable state's intrinsic correlation with causal information is not equivalent to a coding via a signal structure that can be decoded by any means. The transmission of information occurs due to the causal dependence, expressible by Eqn.2. For experiments in a controlled setting, the function of constraint of interaction is known, which is used to evaluate the correlation of the resultant state. For this reason, the semantic value of correlation is considered as a product of interpretation as well as specific to the constraint taken into account. Here, the disjunction of conjunctions

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of states encapsulates all possible specifications of precursor states in reality that may cause the state S of P, hence no specific artificial interpretation is required beyond this generic expression. That is, the processing in modular hierarchy may depend on this fact alone to capture the constancy of relation to build structured and abstract semantics, as shown below. For a neuron, the active state is rather well defined by an Action Potential (AP) that serves as a discrete state and offers a mechanism to cohere with other neurons bearing relatable correlation. Signal structures and neuronal functions may just serve as a mechanism to build coherence and to develop connections as discussed in the text. It resolves an insurmountable problem of coding and complementary decoding via signal structuring to represent increasingly complex and abstract semantics that must respond to dynamic variations. The method of information (semantic) processing vis-a-vis computing[19] is provided by Eqn.2.

2. The physical states transform as per the causal function of the states of interacting systems, not by the information of their correlation; hence information remains intrinsic and non-measurable. Since information arises from the objective causal relation, the causal function of a state in a context creates an opportunity to associate the resultant semantics with the causal function of the semantics of correlation of precursor states (details in Section.5). Therefore, it is entirely possible for a system, processing the information of the causal function of represented objects in hierarchy, to have a state that represents the semantics of 'a system in control of action appropriate for a context' towards a predetermined effect. As an addendum, it may be noted that it serves no purpose to the evolutionary processes whatsoever if the represented semantics does not 'causally relate' with objects to effect change via action. In other words, the evolution of the semantics of self and its purposeful function for effective adaptation and perpetuation could not arise if it was not based on the causal function attributable to such semantics.

3. The basis and mechanism of object description

We begin with a question, "What may constitute a common basis to define a general object such that a uniform mechanism serves as a general constructor of its referable representation?" An object is relatable in two fundamental ways: one, bottom-up structural relations that include components and their inter-relations, and another, top-down functional relations[20] with objects in an encapsulating context. A component naturally includes its own structural and functional relations. While the former is intrinsic, the latter is relative to other objects. Moreover, an object is referable or has an identity by virtue of certain constancy in structural and / or functional relations. Without such constancy in structure or function, there are no definable characteristics, no objectivity, and no referability, hence no existential reality even in the domain of representation (Section.4.1 of [1]). A relation refers to the constancy that holds among objects even when the objects undergo change or transformation. In a broader sense, the 'constancy of relation' refers to the limits of variability or specification of mutual constraint among objects in relation as formally expressed below. An object, serving as a variable, may vary within a certain parametric space of its description, but its identity-defining structural and functional relations must stay within certain limits. The following statement abstractly quantifies the limit of constancy (or variability) of a relation among objects with discrete values. If the number of possible values (states) for an object A is N_A and for B, N_B, yet if the number of possible combinations is less than their Cartesian product $N_A \times N_B$, then the objects are related (expression from[21]), even though for a given value of A, B can have a range of values that forms a class. This expression of relative dependence is extensible to analog variables[21] or to values with arbitrary overlapping extents that can be dealt with conjunction and disjunction as shown in Fig.3.

The constancy forms the basis of an object's identity, be it a physical system, a state description, a relation, an expression, or a process. Specific constancy in an object's structure and function readily suggests how to construct its semantic representation in a modular hierarchy. As shown in Fig.4 and expressed in Eqn.3 (also see Section.3 of [1]), a conjunction of elemental objects, including inter-relations, describes one composition, whereas a disjunction of instances of compositions represents a structured object as an equivalence class that endows it with an identity. This method of structure formation readily suggests the mechanics of integration. As stated above, an elemental object may itself be an abstract or a structured object. For example, a paper possesses a variety of structural and functional relations that remain preserved within limits under transformations. An observable transformation is relative to an observing system, which also includes the identity operation corresponding to no relative change. Under regular transformation of a paper, such as a translation or rotation, several relative properties (elemental objects) remain preserved. The relative placement and orientation of the edges, shape, size, color, texture, reflectance of the surface, as well as the measures of relative distance and orientation of the markings on the surface, remain unchanged. Similarly, the continuity of the edge and the surface remains preserved. Even under irregular transformations, e.g., when the paper is folded (crumpled) randomly, or even cut randomly, the causal continuity in the temporal elemental transformations preserves the correspondence with the prior identity due to the constancy of causal relations. Moreover, the resultant state of the folded paper maintains its own constancy, such as topological continuity, thickness, color, texture, reflectance, mass, and statistical distribution of the folds under further displacements.

Similarly, for a mathematical expression object, $y = \sin(x)$, the components x, y, sin, and $=$ form a structural relation, where x and y belong to a class, $x, y \in \mathbb{R}$, bearing a specific relation such that for each value (state) of x the value of y is unique, and for each value of y, x belongs to a class such that $x = x_0 \pm 2n\pi, n \in \mathbb{Z}$. The constancy of this relation is labeled as a sine function; $=$ is a function object specifying the assignment of the value of the structured object on the right to the elemental object on the left. Hence, the expression object is

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defined by the constancy of structural and functional relations among objects. Moreover, the expression object can be evaluated as a conjunction of semantics expressed by each element, where the elements x and y serve as variables (see Section 8.4 in[1]).

Similarly, ‘right angle’ is a class object that expresses the constancy of a relation between two lines, an instance of which is constructible with lines at arbitrary orientation, where the inter-relation holds. Within the contexts of observation and realization of instances, variation within limits may remain non-differentiable or ignorable, forming a referable class of equivalence. A precision-independent or precision-limited reference to the semantic value of ‘right angle’ as an object functions as a reference to an irreducible abstract discrete semantic value, for it is not equivalent to an instance of a right angle. Moreover, in conjunction with the semantics of the class (space) of relative angles within limits of variation, the referable semantics of ‘right angle’ also serves as a determinator rule when testing or constructing an instance of ‘right angle’. In the physical realization of a mapping system, such as a neural connectivity, the agents whose active state represents the class of ‘right angle’ may map to other agents at higher levels in the hierarchy, where the semantics of the class or relation itself is an element. Depending on the context, the terms for the relation and the class can be used interchangeably. For instance, the term ‘right angle’ refers to both a relation and a class object.

With this understanding, we express the abstraction of structured semantics resulting from a top-down and bottom-up mapping as follows.

$$p\ A\ q_1\ A\ q_2\ O\ p\ A\ q_3\ A\ q_4\ O\ p\ A\ q_5\ A\ q_6\ O\ \ldots = p\ A\ (q_1\ A\ q_2\ O\ q_3\ A\ q_4\ O\ q_5\ A\ q_6\ O\ \ldots) \tag{3}$$

The equation simply exemplifies the distributive law – conjunction, A, is distributive over disjunction, O. The RHS expresses the object p without an explicit dependence on any one conjunction $q_i\ A\ q_j$. For instance, in a bottom-up mapping, each element in a pair may represent a line segment at a particular orientation independent of any other lines at any other orientation, then a conjunction of the two forms a semantics of a composite, which forms a basis of integration ([22]) at each step in the hierarchy. If each of the conjunctions $q_i\ A\ q_j$ bears a common relation p, then the disjunction creates a reference to p without any dependence on or reference to a specific conjunction[1] as shown in Fig.4. A noteworthy point is that the disjunction creates a referable object that does not necessitate a reference to an instance. But in a top-down mapping, it enhances the weight for, or coheres with, right angles over others. Therefore, disjunction becomes a source of emergence, making representation independent of the values of states for the second-order correlation (as per part (ii) of the law). Similarly, in a top-down mapping, a disjunction captures the generic base class object in each of the higher-level contexts (objects) as expressed in Eqn.3 and as shown in Fig.4(d).

A relation among arbitrary objects, including precursors to their causal effect, is expressible as a map.

$$\begin{aligned} F &: \{A, B, \ldots\} \mapsto \{X\} \\ F &: \{A, B, \ldots, X\} \mapsto \{X\} \end{aligned} \tag{4}$$

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Each symbol in the list $\{A, B, \ldots, X\}$ refers to a class or parametric space. A map F defines a relation as a function, where specific conjunctions of values from $\{A, B, \ldots\}$ map to specific values in $\{X\}$, where $\{X\}$ may be a space of composites or higher resolution specifics (Fig.3), or a space of arbitrary relation among values in {A,B,...}. In terms of sets, morphism F is a selection of a subset of $A \times B \times \ldots \times X$. A disjunction of such conjunctions of elements in the subset represents the function / relation F itself. Extensions to the usual interpretation of a map include non-discrete (analog) values that may overlap, spaces that are dependent to include multiple variables covering the same space, and non-exclusive, one-to-many, mapping from domain to codomain, as the function of conjunction and disjunction is independent of such requirements (Section.3.1 of [1], and Fig.3 here). That is, the scheme transparently maps analog, discrete, structured, abstract, and symbolic values to the space of codomain. In a re-entrant system, the current value in space $\{X\}$ can be looped back to form a conjunction with new values in $\{A, B, \ldots\}$ forming a temporal or iterative process as shown in Eqn.5. This also enables a self-referential mapping within limits. Eqn.4,5 present a general scheme to represent a relation computable with conjunction and disjunction and implementable via connections. A population coding method, as presented in[1] and shown here in Fig.3, becomes a necessity to implement such a system with a finite number of elements at the cost of consistency and completeness. In this work, this mapping scheme is used to designate causal, compositional, and reference relations. The first two lines in Eqn.5 symbolize a disjunctive mapping to a single-valued space of function F itself as shown in Fig.4(c), where the LHS includes all specific conjunctions as per the relation F. This amounts to enumeration of all possible conjunctions on the LHS if the values are discrete and finite. For analog values with overlaps or for infinite variations, population coding is required. This creates a reference to the relation F itself, which in turn serves as a functional object with temporal and causal significance in its further mapping. For instance, the third part of Eqn.5 includes the function F as part of the LHS in the prediction of the temporal evolution of values in $\{A, B, \ldots\}$. This mapping scheme forms a recursive constructor in hierarchy without limits.

$$\begin{aligned}
&F_{ref} : \{\{A, B, \ldots\} \mapsto \{X\}\} \mapsto \{F\} \\
&F_{ref} : \{\{A, B, \ldots\}(t-1), \{X\}(t)\} \mapsto \{F_{causal}\} \\
&F_{pred} : \{\{A, B, \ldots, X\}(t), F_{causal}\} \mapsto \{\{A, B, \ldots\}(t+1)\} \\
&F_{eval} : \{\{a_i, b_i\}, +\} \mapsto \{a_i + b_i\} \\
&F_{eval} : \{\{a_i, b_i\}, \times\} \mapsto \{a_i \times b_i\}
\end{aligned} \tag{5}$$

Given the function of the negative range of correlation of a state of agents in limiting the positive correlation in conjunction (Fig.3), it is computationally efficient if the correlation profile of agents varies widely within a module to cover the semantic space, yet dynamically synchronizes within temporal limits via a coherence-building mechanism in order to support the most probable value in the context. That is, the mechanism of population coding presented here predicts diverse tuning (dissimilar initial correlation) profiles and low pairwise signal correlations among the neurons[23][24]. Moreover, the variability in neural response[25] is a part of competitive coherence building[26] rather than a reportable representation of object specification. The current notions of noise and noise correlation in neural activity[27][28] remain misconceived in light of the population coding presented here for building coherence. Moreover, this work challenges the general assumption that specifics of information in the neural system are coded in the spike rate or their temporal structure.

As detailed in [1] and briefed here, ‘disjunction of conjunctions of semantic values’ forms a universal constructor of all expressible semantics. Temporal processes merely include values or functions of relative time in the expression, as shown in Eqn.10 and Fig.6. In a bottom-up mapping to a higher-level object, the disjunction of conjunctions of elemental objects expresses the semantics of a structure, whereas, in a top-down reference, the abstraction of the generic structure and its functional relation form the object specification. Such a reference is clearly evidenced in our thoughts; when one refers to a ‘right angle’ as an abstract object, one does not refer to an instance of it. In other words, in a top-down reference to the object, a sufficiently specific higher-level context must form to down-refer to any particular instance of an object at a lower level. Since this holds at each step in the hierarchy, agents in higher-level modules have a much wider sensitivity to encompass all possible specifics representable at lower levels; at a given moment, though, the bottom-up construction determines the integrated value the higher-level agents represent. The graphical examples in Fig.4 illustrate the mechanisms of conjunction and disjunction as bottom-up and top-down constructors of structured and abstract semantics.

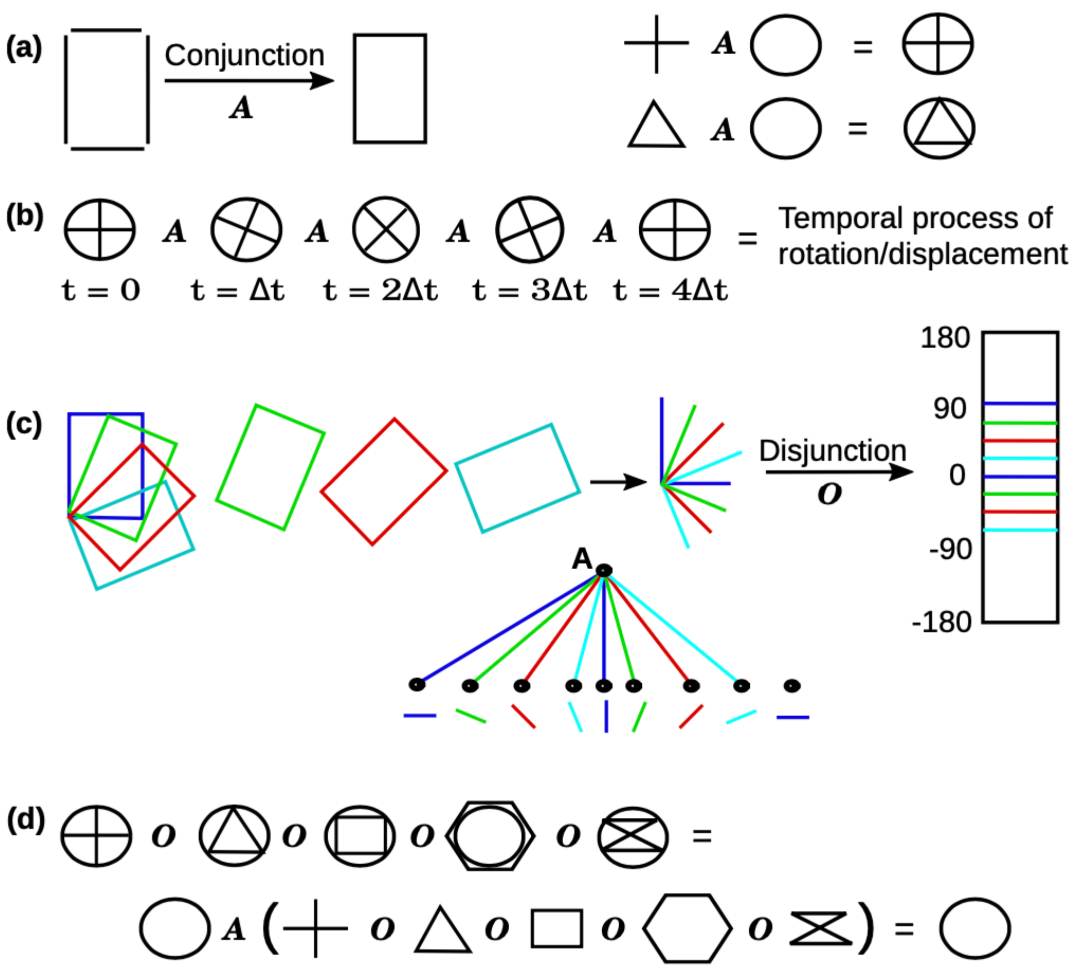

Figure 4. A graphical illustration of methods of conjunction and disjunction on semantic values; conjunction captures the composition, while disjunction gives rise to an abstraction of a class or a relation. Each of the panels a, b, c, and d is organized horizontally. **(a)** A conjunction of 4 line segments appropriately placed forms a rectangle. On the right, features in specific relation form composites. **(b)** One of the composites in (a) undergoes a regular transformation sustaining an internal relation among its components. A conjunction of events in temporal sequence forms a temporal event or a process. **(c)** When a rectangle undergoes a rotation about one of its vertices or a rigid displacement, the neighboring two sides (line segments) maintain a relation of right angle as shown on the right. A mapping of each conjunction of two lines on the orientation space (displayed vertically) is shown as horizontal bars in the same color. A disjunction of all such combinations that covers the orientation space gives rise to an emergent semantics of 'right angle', an abstract semantic value with no physical counterpart. The same mapping is also shown as a network of connectivity from a set of agents (such as neurons) that represent line segments at specific orientation to a higher-level agent A, such that each active conjunction in the map, shown in the same color, may activate the agent A. The active state of A then represents the irreducible semantics of right angle that emerges from a bottom-up mapping here. **(d)** A series of composite (structured) objects may share a common feature; a disjunctive

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relation among such objects evaluates to the common feature as a base class as expressed in Eqn.3 and 6, without any particular dependence on another feature in each conjunction.

As shown in Fig.4(a), a conjunction of 4 line segments of specific width and length in specific relative position and orientation forms an instance of a rectangle, where any two adjacent lines form a right angle. This structured object (rectangle) may form an element of yet another object, e.g., a paper. When a rectangular piece of paper rotates about a point or undergoes displacement, its four edges (lines) sweep through orientation space, but the relation between any two adjacent lines remains preserved (invariant) under the transformation as schematically presented in Fig.4(c). Consider for a moment different active sub-populations of agents in module M1 representing different line segments mapping to another module M2. The agents in M2, receiving inputs from M1, can be dynamically constrained in a re-entrant network to build a sustainable coherence over time among a sub-population. A sustainable coherence is possible only if the population competitively represents a feature or relation that remains invariant over time, as suggested in Eqn.5 and discussed in Section.3.1 below, which is the relative angle between the lines here. The term 're-entrant network' is used to refer both to local recurrent loops within a module as well as to feedback connections from other modules. The specific case shown in Fig.4(c) is idealized as a static map, whereas it is a population-coded dynamic map in a re-entrant system.

In each of the illustrations in Fig.4, the represented objects may be limited in resolution or may have non-discrete overlapping descriptions. That is, Δt in (b), and the orientation of line segments in (c) may have a width of resolution to cover the temporal or orientation space with a finite number of elements, but the method of population coding sharpens the specification as shown in Fig.3. The methods apply universally to all semantics or objects, as conjunction and disjunction are type- or category-independent operators. Moreover, a mapping system may capture an arbitrary relation – e.g., a mapping of two values from the space of numbers to the space of numbers may represent the relation of sum, difference, product, or any other if observed consistently. That is, a difference relation is achievable via mapping, not necessarily by a mechanism of differentiation.

At this point, we note that the active state of an agent functions as a reference to represented semantics. The agents representing different elements of an active context turn active in close synchrony of time. As the paper incrementally transforms relative to an observing system, the constancy of various relations provides ample opportunity to self-organize the activities of agents in a modular hierarchy to connect the temporal sequence of activation at one level to a specific set of agents at the next level under the population coding scheme. Such activations strengthen the connectivity on the recurrence of the same relations while pruning any randomly

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occurring correlations based on statistical significance. In the limited domain of observation, an emerged class is not complete, yet it serves as a class descriptor in its further mapping.

An object specification may also emerge from a top-down process from objects of greater complexity and from relations in an encapsulating context. Consider a structured object S_1 describable as $(p_1\ A\ p_2\ A\ p_3\ A\ \ldots)$, where $(p_1, p_2, p_3, \ldots)$ are descriptive elements. Similarly, another object S_2 can be described as $(q_1\ A\ q_2\ A\ q_3\ A\ \ldots)$, where one of the components, say q_1 is equivalent to p_1. We may replace q_1 with p_1 in the expression of S_2 to get $(p_1\ A\ q_2\ A\ q_3\ A\ \ldots)$. Now, the disjunction of all such structured objects S_i, where p_1 is the common element, can be evaluated as per Eqn.3.

$$(S_1\ O\ S_2\ O\ \ldots) = p_1\ A\ ((p_2\ A\ p_3\ A\ \ldots)\ O\ (q_2\ A\ q_3\ A\ \ldots)\ O\ \ldots) \tag{6}$$

As per the evaluation method provided in Table.1, since there is no common element among the terms in disjunction within the parenthesis on the right-hand side of Eqn.6, it amounts to no particular dependence on any one of the terms, a null correlation with each instance, reducing the correlation to p_1. This is how a disjunctive relation expresses the base class element common to all terms. In fact, in the extreme atomic case, the functional relations are the only way to refer to an object, as for a structureless charge, mass, or a point in the visual field. In strictly top-down references, all objects serve as atomic. The method is visually presented in Fig.4(d). Similarly, the objects where an instance of a right angle manifests are papers, tables, walls, doors, windows, trees standing vertical to the ground, etc. Each of these objects can be expressed in the form of a conjunction of specific elemental objects, where the right angle is one of the common elements. If the common element is a structured class object, it may have a bottom-up reference to the object in addition to the functional relations as discussed above for the right angle class, but this is not a necessary requirement.

3.1. Representing structured relations and temporal events

As suggested above, processing is organizable in a modular hierarchy, where a module is shared among, or connected to, several other modules via feedforward and feedback projections[29]. A module is a densely connected recurrent localized network of elemental agents[29] to process and represent the structure present in the dynamics of objects represented by the active states of projecting agents from other modules. It is then possible to designate locally lower, higher, and equivalent level modules based on the mapping configuration such that the higher-level modules represent more complex and abstract semantics. Each module serves as a structured parametric space. The neural organization of the brain is an instance of the scheme; it must have the following characteristics. Since the disjunction of conjunctions of countably finite elements forms a constructor of a singular semantic value, it requires the agents to have a singular (discrete) output state to represent the expressed semantics; here, we refer to that as the active state, such as an action potential of a neuron. Moreover, since the output of an agent is distributed among many agents for coherence building, the information flow between two agents must only be one way to avoid direct and non-linear mutual dependence in an interaction. Similarly, since a module receives input from several modules representing elemental specifics, a context becomes specific and sparsely distributed; a tree-like branched structure is rather suitable to receive inputs to map closely related elements of a context with a greater probability of occurring together in close proximity on the branches for greater cohesion[22][30][31]. Therefore, the observed anatomy and function of the neurons provide strong evidence that the neurons emulate the constructor expression advanced here.

The artificially devised mechanisms of exchanging information are based on encoding information and communicating the same to other agents that must already have information that the codes correspond to [32]. This is also the case with linguistic communication between two individuals. The function and organization of our brain implement a mapping that uses the terms as a reference to semantic values, where terms are communicated via graphemes and syllables. The artificial systems often re-encode the linguistic terms for communication[32] that is decoded to recover the terms, but their mapping to the semantics is left for a system like the brain. Demanding a similar coding system from neural function in terms of signal structure misses the point that the codes must be mapped to the semantics. Such a demand misdirects a scientific question, limiting our abilities to investigate the representation and communication of semantics via intrinsic causal correlation. In the paradigm presented here, the states of agents bear intrinsic correlation with the semantic content of information of the context, which is not decodable by an external agent. However, the coherence in the semantic elements of a context reflects in coherence in the active states of agents that causally correlate with them. A coherence among their active states presents an opportunity to capture and represent structured semantics in terms of disjunction and conjunction of elemental values.

As noted above, the construction and referability of an object are based on the constancy of its structural and functional relations in the dynamics of change. This basic principle serves well to create and represent all objects (relations, processes) in a context via mapping. One may recall that a correlation profile is specified by the limits of positive, negative, and null correlation with a range of values in specific spaces of semantics (see Fig.3). Therefore, the greater the coherence-based conjunction, the greater the specificity of the represented object in the context. The active coherence must be further sustained to follow continued relevance in an evolving context. Now, if each of the modules in a system carries out the same task of representing the constancy of structural relation among elemental objects of lower-level modules and functional relation with objects of higher-level modules, then one has a universal mechanism to construct all semantics (objects) in hierarchy, which includes their function in the domain of representation.

A specification represented by the predominant coherence among agents with varying correlations in a context, in opposition to other such possible coherence, must be the most likely an object in its neighborhood. For instance, in the presence of a right angle in a context, coherence in the neural activity representing the right angle, in contrast to other angles, is likely to be predominant based on feedforward and feedback signals from a multitude of parametric spaces. That is, only reality can be consistent when observed multiply! The greater the specificity of the relative description, the more specific the action possible towards a goal. A goal-directed action may require a certain degree of specificity, where greater specificity may not serve a purpose. For example, the need to displace a physical object by a few centimeters with a precision of a centimeter does not require greater resources to be recruited to move by a millimeter precision. As suggested by the population coding mechanism presented in Fig.3 and Section 7 of [1], finer resolution (precision) may require greater coherence and conjunction among a larger number of agents, and greater loopback processing.

Similarly, in the dynamics of change, the specification of a temporal object, such as a rate of change or a sequence of events, that continues to stay relevant for the duration of the context in contrast to other objects or processes in the neighborhood, must be the most suitable specification of the object or process. For instance, consider the swinging of a branch in the wind that one attempts to hold. A prediction of movement with greater precision may not hold for long, and a long-range prediction may not be accurate. As the approach closes, the specificity of prediction must improve. In the dynamics of change, greater specificity may be relevant only for shorter times, while lower specificity may not suffice for goal-oriented action. Such a relevancy contrast requires a dominant coherence among the active states of agents to stay relevant and dominant with time in a re-entrant system. Since the coherence relation is captured from the temporal dynamics, the configuration of active states of agents at one moment must loop back to strengthen the configuration at the next [33], (Eqn.5). Therefore, if a dominant coherence of a moment is looped back and stays in coherence with the incoming signals at the next moment, it represents the most relevant constancy of a temporal process within the modular space. Hence, a continued competitive coherence in the re-entrant network becomes a requirement of the function in modular organization. The constructor expression serves well to represent temporal coherence among agents with discrete signaling, such as action potentials. Recall that a conjunction of events at contiguous steps in time represents the structured temporal object as referred to in Fig.4(b), depicted in Fig.6, and expressed in Eqn.10, where the conjunction builds via a loopback mechanism. Moreover, a disjunction of variations of events at each instance allows a class of process specifications to be represented. Since all observations are necessarily temporal even when the objects do not change, the mechanism of temporal coherence (synchronization) among the transient states of agents remains general to represent relations in the dynamics of objects (variables) as observed in neural systems. The continuity of time and space, the uniform function of their intervals, and the speed of signal propagation are a few of the fundamental constancies of relation that provide a robust basis to observe other structured constancies in natural phenomena.

The process of population-coded competitive coherence over time has a few immediate implications. First, the evolved mapping based on the population-coded constructor expression functions as the causal predictor and

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effector of the semantics of the next moment (See Eqn.5,7). Second, since the function of an object is dependent on all causally relevant objects in a context, the context-relative functional relations of each object get represented, where each object also plays a part of the context for other objects. The function of a structured object is also defined by the function of its components; hence, the relevance of each component in a context increases the relevance of the structured object. Third, in this process, a powerful mechanism emerges from the fact that in a given context, the system makes available even those causally correlated semantics from past experiences (memory) that are relevant but not part of the current observation[34]. In common parlance, this is often referred to as understanding of an object in opposition to the single-threaded semantic dependence and processing in artificial technologies of the present times. Fourth, it also enables a system to recall element-wise correlations in a new context to build coherence and to generate the most probable prediction, which has the power of graceful degradation even in novel contexts. The larger the number of elements in a context, the lower the probability of a bad prediction.

A prediction is necessarily based on the constancy of causal function. A contextual state in the environment naturally evolves to the next state as per the causal function of the elements in the context. The temporal evolution of objects follows their causal dependence on objects of context, which can be used to create a population-coded re-entrant mapping system, where a configuration of active states of agents representing the elements of the context at one moment enhances the coherence of the configuration representing the context at the next moment, as expressed in Eqn.7. An idealized mapping system is illustrated in Fig. 5(b). For a dynamically evolving mapping system, instances of active mapping from one moment to the next capture instances of the causal function of the objects. A disjunctive relation among such mappings represents the semantics of the causal function specific to the object space, as per Eqn.5. For example, when bringing together two groups of elements into one yields the sum of elements in the resultant group, the disjunction of such mappings within observable limits represents the semantics of the function of joining groups or summing. Moreover, since such causal relations are representable in multiple relatively higher-level modules for their relevance, a disjunctive relation among such space-dependent causal functions would then represent a space-independent referable semantics of causal function (causality) itself in a yet higher-level module where it may be relevant for higher semantic structure. This mechanism of abstraction exemplifies how arbitrary semantics of conceptual entities emerge without a dependence on specific object types.

$$\begin{aligned} &F_{causal} : causal\_precursor \mapsto causal\_consequence \\ &F_{causal} : \{A, B, \dots\}(t) \mapsto \{A, B, X, \dots\}(t + \Delta t) \\ &F_{ref-causal} : \{\{A, B, \dots\}(t) \mapsto \{A, B, X, \dots\}(t + \Delta t)\} \mapsto \{F_{causal}\} \end{aligned} \tag{7}$$

Since there is no mechanism of coding and decoding of information by signal structure, how could a system construct a representation of structured semantics in a modular hierarchy based on the constancy of causal

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relation? The only way useful functions of objects may get represented is by the measure of success of action / behavior towards certain evolving goals in line with the selection pressure from the prevailing context. This, in turn, requires that the predictions from learning via multiple sensory modes find conformance with each other and with action. Therefore, the evolutionary processes favor the self-organizing functional architecture that models the environment based on the constancy of relations to select self-sustaining action. The same mechanism can be used to develop artificial systems of processing without specific coding for learning.

In a modular system, specific states of agents in a certain set of modules, M, may evolve to represent the physical states of the holding body (the body that sustains the system of processing) that are in accord or conformity with the requirements of selection. For biologically evolved systems, such modules may represent the conditions of well-being of the body consequential to the sustenance of the system of processing. In mammalian brains, these modules are located in old sub-cortical regions[35][36]. For an artificial system under arbitrary causal function, such states may even be externally coded. For the consideration here, it is immaterial how the processing system represents the states of suitability. The conditions of suitability may be multi-dimensional and graded. The net effect of the active states of agents in modules in M on the rest of the processing system, S, is to select specific processing and action that are aligned with the suitability conditions[37][38][39]. Now, given the abilities to represent higher-level abstract semantics in S, the descriptions of suitability of function and states of the system may emerge in S (say in a cortical brain, for instance[37][40]), which may bidirectionally map to modules in M[37][38][39] and evolve in tandem such that M's function is based on higher-level semantics rather than just on the physical states. Modules in S may represent higher-level referable semantics, together serving to select specific processing and action[35][38][41][42]. That is, these referable semantic values serve as preferential biases (goals), such that their activation serves to modulate, strengthen (promote), or weaken (demote) the competing processes of relevance for action (behavior) in different modules. The satisfaction of the biases may depend on what is observed on the holding body and within the system of representation itself. Since the biases are referable, a causal relation between the biases and the behavior is further representable as per Eqn.7. Furthermore, the semantics of biases may express even explicit negation of other semantic values, allowing the classes of semantics of likes / wants and dislikes / unwants to emerge when these semantics relate to the representation of self, as shown in the next section. Such classes of preferences in relation to the represented self function as guiding principles or emotions[38][41][42], and serve to enhance self-preservation. Moreover, the process of promotion and demotion may proliferate the semantic classes of likes and dislikes in every module that has an effect on action to the extent that every external action depends on the convergence of such choices. Furthermore, S and M may produce physiological effects and arousal[43][44][45] that are either fed back into S internally or observed on the body and related with the semantics of emotions – another pathway to control function and behavior.

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Such semantics of biases (goals) are a product of evolution, which plays a critical role in the development of systems with the ability to represent arbitrary semantics with causal powers of selection and action. The biases emerge in response to varying selection pressures arising from diverse but specific environmental contexts; they are not expected to be functionally and optimally consistent in all possible contexts. It is not important here whether such modulations of competing coherence are effected via chemical means in a biological system or via a strict signaling mechanism.

In summary, representing the semantics of structured relations among objects gets translated into capturing the optimally probable dynamics among agents in a re-entrant network via a coherence-building mechanism in opposition to other probable dynamics in input states of agents as historically observed. As per the observation above, a goal-directed action requires merely a sufficiency of relative specification among competing descriptions, not necessarily the one with the sharpest specification. A sharper specification of a relation in the context may require a larger number of elemental agents to form a coherence, and multiple looping back of signals to achieve greater synchrony as suggested in Section.7 of [1]. Therefore, there exists a trade-off between greater specificity and the amount of resources required for functionally optimal behavior. The representation of causal relation as presented here (Eqn.7) forms a central mechanism at all levels. In addition, it is noted here how the referable biases and goals may emerge in such a system of processing that controls function and behavior.

It is not the purpose here to identify specific physiology, function, and types of neurons in the brain and their connectivity, but rather to lay down the specific mechanism of information processing leading to the representation of the semantics of self and its relation with the objects, of which the brain is an instance. The specific mechanics of constructing object descriptions provide sufficient ground to construct semantic components of self.

4. The semantics of self as an element of represented objects

The correct identification of the object of a scientific investigation is as important as the construction of its objective formulation. In an expression like, “I see the blue sky,” what does the ‘I’ refer to? The representation of self is an object like any other, even though in common reference to consciousness, either it is ignored or it holds an asymmetric status with other objects as if there is a fundamental qualitative difference between the two[13].

4.1. Spatial relative placement of the observing system

First, we construct a representation of the spatial placement and temporal movement of an observing system in relation to other physical objects observed in space and time. Consider a system capable of correlating or mapping relative times of signal propagation to relative constancies in natural function, such as mutual distances and angles of placement of objects with respect to the system's direction of movement in a 2-dimensional Euclidean space (field). Further, consider a few objects scattered in the field at $(r_i, \theta_i, s_i, i = a, b, c, \dots)$ with respect to the observing system at a given time. Here, r_i is a measure of distance, θ_i a measure of angle with respect to the direction of movement, and s_i the side of placement of objects, Left, Right, or Inline. We may label the placement of the objects independent of a coordinate system symbolically as $(x_i, y_i, i = a, b, c, \dots)$. For the moment, these labels merely serve as symbolic names for different points without any reference to a coordinate system. The idea here is that if points in space and time, and distance and duration, play any causal role in the function of the universe such that events at different points in space and time cause mutually relative differential consequences, then these labels serve to identify and relate the points by their mutual relation in the consequence. For instance, if a short pulsed narrow frequency signal of an event originates at the system and travels in space as per the reality of natural function, then the signal traverses through all objects. If the objects serve as signal reflectors, then the system at the origin of the event would receive back the reflected signals in a certain temporal order. Measures of relative time of signal travel form the measures of spatial distance to these objects by virtue of the constancy of the speed of signal propagation, as shown in Fig.5.

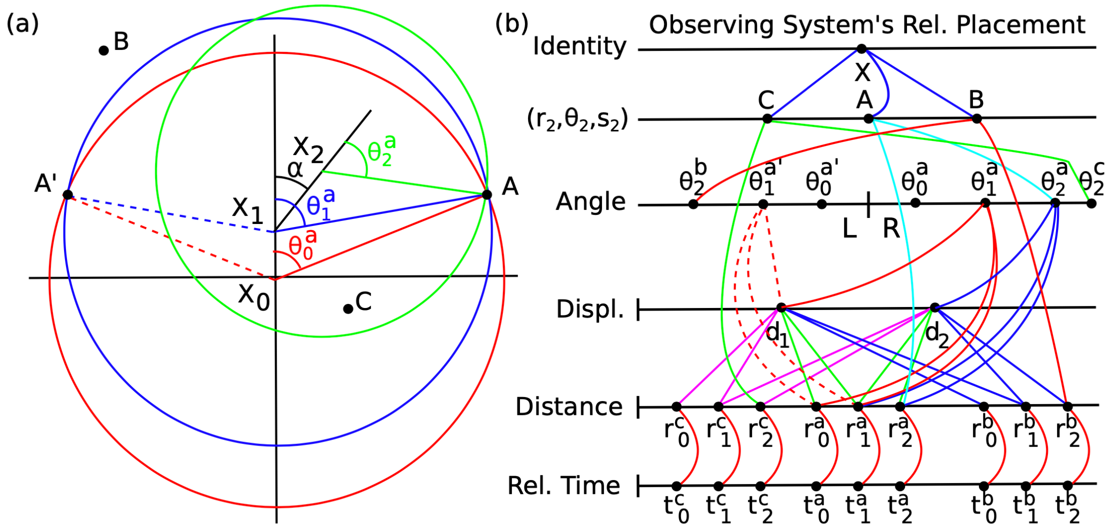

Figure 5. A graphical illustration of a mapping scheme. **(a)** Objects $\{A, B, C\}$ are shown in a two-dimensional spatial field, where system X serves as an observing and mapping system to represent the relative placements. A signal originating from X at location X_0 is reflected by $\{A, B, C\}$ and received back by X at relative times (t^a_0, t^b_0, t^c_0) respectively, that further map to respective distances (r^a_0, r^b_0, r^c_0) in one-to-one mapping as shown on the right, where the index in alphabet represents the object and in numeral the measurement number. For instance, the placement of object A can be anywhere on the circle in red centered at X_0. As the system X moves to a new location X_1, it regenerates a new signal with a different pulse duration or frequency and receives the reflected signals back at relative times (t^a_1, t^b_1, t^c_1). Now, the locus of object A is shown with a circle in blue centered at X_1. The cross-section points of the red and blue circles fix the location of A with respect to both points X_0 and X_1, before and after the movement; the symmetric placement of A about the line of movement is shown with dashed lines leading to A'. The second movement of system X to X_2 at an angle α with respect to the first movement and a new set of measurements of reflected signals fixes the location of all objects in the field uniquely as analyzed in the text and shown graphically with three circles for object A. The angles θ^a_0 and θ^a_1 are values of correlation for object A relative to two ends of the first movement, while $\theta^a_1 - \alpha$ and θ^a_2 are to the second. **(b)** Labeled parametric spaces are shown as black horizontal lines, whereas labeled nodes shown as big dots on them represent discrete values. Colored lines converging on a node from below represent incoming projections from lower parametric spaces. Similarly, the lines emerging upward from a node designate forward projection, which bears no color correlation with incoming lines. The lines shown in the same color converging on a node from below represent a conjunction of values represented by the projecting nodes, whereas a convergence of multiple such conjunctions in different colors on the same node represents a disjunctive relation. The angle space is marked with L and R to indicate Left or Right of movement, or the sign of the angle. (r_2, θ_2, s_2) labels the composite space of distance and angle for different objects. The node in the top parametric space represents a disjunctive convergence of conjunctions of relative placement of any three objects observed in the field at all times; only one conjunction is shown in the figure. This node represents the

placement of the observing system X itself relative to objects in space at all times, and forms a component of the system's identity.

In Fig.5, the perspective of the parametric mapping is based on system X. It is assumed here that the signal travel speed is much greater than the speed of X. As a first approximation, we take the displacement of X to be negligible while reflected signals are received back from nearby objects. Since the active state of an agent in an array is said to represent the time interval since signal generation, which causally depends on the speed of signal travel, the state directly correlates with distance. Moreover, the distance traveled by X between two signal generations is also assumed to be relatively small with respect to the inter-object separation in the field. This implies that the two closely spaced measures of time from two consecutive signal generations are from the same reflector, hence, conjugated together. This places a limit on spatial resolution. These approximations are not required when the number of objects in the field is larger than three or when prediction from past observations is used, as shown below. For one-to-one correlation with distance, the relative times of signal travel are mapped to distance space on a one-to-one basis in Fig.5(b). Eqn.8 expresses the displacements of the system X by d_1 and d_2 at intervals of signal generation and angular displacement α.

$$\begin{aligned} &r_0^a cos(\theta_0^a) - r_1^a cos(\theta_1^a) = d_1 \\ &r_0^a sin(\theta_0^a) - r_1^a sin(\theta_1^a) = 0 \\ &r_1^a cos(\theta_1^a - \alpha) - r_2^a cos\theta_2^a = d_2 \\ &r_1^a sin(\theta_1^a - \alpha) - r_2^a sin\theta_2^a = 0 \end{aligned} \tag{8}$$

Here, the indices in alphabet identify the object, and in numerals, the measurement number. The same equations hold for all reflecting objects. The values $r_{0,1,2}^a$ are known at the respective points of measurement. The sine is an odd function, and cosine is an even function; hence, a sign inversion in the argument angle is a degenerate solution, as shown with dashed lines for object A in the figure. A set of four equations for each object adds three unknown angles θ_i, where $\alpha \neq n\pi/2$, d_1, and d_2 remain common among all objects, requiring at least three objects to match the equations to parameters. A conjunction of two relative times or distances from two consecutive measurements for each object not only correlates with the angles at each point of measurement but also with the measure of movement of X common to all objects. A conjunction of three distance measures for an object correlates with all parameters of relevance here, Eqn.9.

$$\begin{aligned} &(r_0^a\ A\ r_1^a) \Rightarrow ((+\theta_0^a\ A\ +\theta_1^a)\ O\ (-\theta_0^a\ A\ -\theta_1^a))\ A\ d_1 \\ &(r_1^a\ A\ r_2^a) \Rightarrow ((+(\theta_1^a - \alpha)\ A\ +\theta_2^a)\ O\ (-(\theta_1^a - \alpha)\ A\ -\theta_2^a))\ A\ d_2 \\ &(r_0^a\ A\ r_1^a\ A\ r_2^a) \Rightarrow \theta_0^a\ A\ \theta_1^a\ A\ \theta_2^a\ A\ \alpha\ A\ d_1\ A\ d_2 \end{aligned} \tag{9}$$

Where, $\Rightarrow$ stands for 'correlates with'. Here, the conjunction on the LHS serves as a multi-valued function, where the values in conjunction can be thought of as arguments to the function. The conjunction on the RHS is consistent with the sign (L,R selection) for θ_1^a for a non-zero value of α. Sufficient information exists in the

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system to create modules for the parametric spaces shown in Fig.5(b). The inputs received by a module fix the parametric space represented by the module. The process of competitive coherence building under the population coding scheme, as discussed above, among modules of these parametric spaces, would converge to unique values for all correlated measures of angles and movements. It is evident that the greater the number of objects followed, the greater the accuracy and precision achieved under the scheme. The values for d_1 and d_2 are common to all objects in Eqn.8; they are shown as a product of a disjunctive relation as per Eqn.6 in a bottom-up mapping in Fig.5(b) for simplicity. The conjunction of two measures of distance and the respective movement of X correlates with unique magnitudes for the angles at both ends.

$$r_0^a \; A \; r_1^a \; A \; d_1 \Rightarrow \theta_0^a \; A \; \theta_1^a \quad \text{and} \quad r_1^a \; A \; r_2^a \; A \; d_2 \Rightarrow (\theta_1^a - \alpha) \; A \; \theta_2^a$$

The first two distance measures of objects correlate positively with the respective $\theta_i^{x'}$ as well, but the third measure correlates negatively with it. Therefore, the conjunction of three measures for each object correlates negatively with all angles except θ_i^x. To avoid clutter in the figure, the mapping is shown only for the object A.

A relation that is very relevant for action in nearly all placement contexts is a conjunction of measures of (r_2, θ_2, s_2), where s_2 denotes the sign or the (L, R) value for θ, for it uniquely specifies or represents the placement of the system itself with respect to any three objects as shown in the diagram. While the values (r_2, θ_2, s_2) may continuously change for each object as the system moves in space and time, a conjunction of three continues to cohere with the placement of the observing system itself. If there are n reflecting objects in the field, then there are ${}^nC_3$ combinations that ideally represent the same common information. Given the redundancy, a system may build or select a greater coherence-based conjunction to gain specificity. If a system has multiple measures for the same quantity, each with an independent resolution limit, then a larger conjunction of such measures significantly improves the resolution as shown in Fig.3. Even though the distances and angles of other objects are represented in system X, the same angles and distances are mapped to a modular space that represents the placement of the observing system itself, making it referable within the system, which forms a part of its own identity-defining relation.

A few points are noteworthy. In real systems, a number of agents represent overlapping limits of values in the population coding scheme presented here to cover a semantic space, but here, nodes represent discrete ranges of values covering the space, which makes it convenient to show a relational feed-forward mapping among nodes with lines. Moreover, in a hierarchical re-entrant system, these mappings are dynamically constructed from competitive coherence relations among signals received to capture relevant constancy in observed phenomena as discussed in the previous section. But here, it suffices to show how relations describable by conjunction and disjunction correlate with values in different semantic spaces. A space gets defined by a mapping given by the constructor expression on the values from different spaces. Lower-level elemental objects define structure, and higher-level contextual objects define the limits of relevance as implied in Fig.4(d).

It is apparent that the same mechanism remains applicable to all measures in observed phenomena if they are relevant in contexts. In the example discussed above, measures such as spatial and angular displacements of system X, d_1, d_2, α, are represented. If the signal generations are periodic at constant intervals, then the same measures also serve as (or map to) rates of their respective changes, for the divisor remains a constant. In fact, each measure of distance arising from the consistency of feed-forward and feedback coherence and relative time may also map to the measure of speed of signal travel as it is relevant for prediction. If the number of objects in the field is much larger than three, then the population coding method not only achieves higher resolution or precision of specifics as per the need but also provides resolution to the combinatorial problem while allowing incremental changes at all times based on statistical coherence without undergoing a complete reset of the mapping system. Such a system is robust against a degree of deviations and errors because the system of processing is based on competitive coherence. Forward and feedback mapping from related parametric spaces along with the previous measures in each of these spaces correlate with the new measures sustaining coherence in a re-entrant system. For instance, the conjunction of rates of displacement of the observing system in space and in angle along with the previous measures of distance and angle of objects' placement in periodic sampling correlates with the next values of objects' placement. In fact, the inter-signal interval need not be a constant if it is represented in a parametric space of its own and forms a factor in conjunction.

In a hierarchical organization of processing, higher-order derivatives of change are representable with variations in lower-order derivatives if relevant enough for competitive coherence for successful predictions. With the availability of parametric rates of change in measures resulting in forward predictions of measures, neither of the two approximations stated above is required. Moreover, sustainable deviations from prediction correlate with the external changes in the context. For example, when the objects in the field move, the displacement is captured via difference relation from coherent prediction for all objects, and the derivatives of change are mapped and represented, which then become part of the next prediction, and so on. A noteworthy point is that the observing system may continue to follow the movement of objects in relation to other objects and map onto the same node in a parametric space that serves as the space of identities for respective objects as shown for the system X in Fig.5(b).

We note from Eqn.8 that the cosine expression gives the same result for all objects, and the respective sine expression yields a value of zero for all. It is natural to expect that these constants, relative to the movement of the system, may form parametric spaces of their own. We also note that a given displacement of an object, irrespective of its current location, merely corresponds to a constant addition of values in these parametric

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spaces that the cosine and sine expressions yield. Now, the labels (x_i, y_i) are meaningful as measures of distance along axes that define the Cartesian coordinate system. There is no necessity to begin with a reference frame; a relative frame emerges from correlations. Since relations are constructible with respect to any arbitrary point or direction in space depending on its relevance in coherence building and prediction, all such frames are equivalent. A third-person perspective is merely an arbitrary fixation of a frame. Therefore, it is always possible to choose one arbitrary but convenient reference frame to place all objects with respect to it to draw certain specific inferences, which is often the case in scientific analyses.

While this specific example serves as a simplified illustration of a mapping system, it also serves as an idealized system of echolocation. In fact, the mechanism stays true for all parametric (object) spaces, making available a uniform mechanism of object description. For echolocation, distances are observed that correlate with angles, whereas for vision, angles are observed that correlate with distances. Since the constancy of relation is the basis of representing an object, and every relation is captured via the interaction among physical substratum quantified by the constructor expression, all represented objects have causal consequences.

4.2. Representing a system as an actor, observer, and controller

When a physical system interacts with other systems, it undergoes a transition in its state in response to the causal states of the interacting systems, Fig.2. Hence, all physical systems function as a sensor and effector. A neuron functions as an elemental agent that receives discrete action potentials (APs) as input from a large number of other neurons and generates an AP, which is then distributed to a large number of other neurons as per the dynamically evolved connectivity. A neuron turns active when there is sufficient coherence in the input signals, where signal coherence is based on the coherence in the semantics of elements of the context represented by the active states of presynaptic (projecting) neurons. An inhibitory input serves to raise the requirement of even greater coherence (conjunction) of excitatory signals in number and in temporal synchrony for activation as part of a competitive organization, effectively narrowing the limits of positive correlation while widening that of negative correlation (see Fig.3). If inhibition succeeds, then there is no further communication from a neuron in the network. Naturally, the mechanism applies to all sensory domains and their integration. The problem then reduces to representing the semantics of the function of being an observer of objects and an effector of change to the objects, as they are rather dominant correlations for their suitability for behavior.

We recapitulate the basis of construction of all semantics. An element of semantic value specifies a profile of range of values with positive and negative correlation. A conjunction of such semantic values evaluates to greater specificity in the range where the profiles overlap among the operands, and extends the profile or composition where they do not, i.e., when for a given range or domain one of the operands has null correlation.

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A disjunction expresses the generality of a class that includes a range of instances, or a relation as a descriptor of the class, an abstract value. Structural integration occurs when a conjunction binds components together[22] into a composite, and the disjunction generalizes the variations into a class of structure (see also[1][46][47][48][49] on binding). A structure or a class at one level relates as an element at the next higher level. The function of an object is defined by its relation with other objects that determines the consequence in a context. Functional relations constitute elements of a structure in a modular hierarchy. The constancy of structural and functional relations forms the basis of all descriptions, their referability, and a general mechanism to construct all object specifications uniformly (systems, relations, processes). In addition, the mechanism of population coding enables a self-organizing system to evolve with incremental changes based on observations of statistical correlations, and to represent a large dimensional object space with greater specificity with far fewer agents and their intrinsic states. These correlations form the basis of functional and temporal prediction in re-entrant systems, allowing continuous correction to achieve goal-oriented sufficiency of accuracy. Since there is no limit to higher-order complexity of structure formation and abstraction of semantics, a system like the human brain has evolved deep layers of hierarchy and wide modular object spaces to represent very complex and abstract semantics and their causal relations. Moreover, there is no unique pathway for constructing the representation of self and its relation with other objects, as is evident from the existence of a multitude of species with different modular neural organizations. Hence, the idea here is to construct a description that resolves only the essential issues in representing the self and its relation with other objects.

Active states of agents of inter-modular communication may represent gradually more complex (structured) semantics in hierarchy. For instance, from pixelized points in the field of view to line segments, from lines to specific contours, and from contours to specific shapes may emerge that are independent of space, time, color, contrast, and other qualities that may additionally be associated with them. Similarly, the semantics of inter-object relations, such as relative time, location, orientation, size, motion, and visual contrast, may emerge. Similarly, inter-modal structures may emerge from different sensory systems. Similarly, the relative rates of change in different object spaces may form elements of structures. Similarly, the representation of temporal processes (episodes) may form elements of the observed dynamics. A conjunction of events at regular intervals of time in a temporal sequence binds together the events to form a temporal event or a process as depicted by Eqn.10 and shown in Fig.6. Then, the subsequent active state of agents that depends on this conjunction in a re-entrant system would represent the semantic value of the prior sequence or process, including the temporal relation among the events ([50]). As the semantic structure of events at each interval includes certain limits of variation within the parametric spaces of description equivalent to a disjunctive relation, the conjunction of events represents the process as a class with diminishing (less specific) correlation with events in the past.

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$$
\begin{aligned}
&v_1 \; A \; v_2 \; A \; v_3 \; A \ldots = \underset{i}{A} \; v_i \\
&v_1 \; O \; v_2 \; O \; v_3 \; O \ldots = \underset{i}{O} \; v_i \\
&E_i(t_i) = \underset{j}{O} \;\; \underset{k}{A} \; v_{jk}(t_i) \\
&TEvent_i = E_i(t_i) \; A \; TEvent_{i-1} = \underset{i}{A} \; E_i(t_i)
\end{aligned} \tag{10}
$$

The first two lines in Eqn.10 establish the symbolic convention used here. $E_i(t_i)$ denotes the i^{th} event in the sequence bounded within relative time t_i, which is a disjunction of conjunctions of values from parametric spaces of relevance. The last equation expresses that a conjunction of semantics of such events in temporal sequence is a temporal event, a process. One of the variable parameters of correlation is time relative to the neighboring events, which positively overlaps with them minimally, and bears a negative correlation with the rest of the space as depicted in Fig.6. That is, t_i carries positive correlation only with the range $t_{i-1} < t_i < t_{i+1}$. A simple mechanism to enforce a temporal order is the dependence on prior coherence among active agents in each module, and the subsequent activation being aligned with the next coherence at regular intervals. Then the continued conjunction of such events maintains temporal order among events as well as their continuity without a hole as one continuous process over the entire duration. This constitutes a general mechanism to represent continuity in a parametric space of observation, as also exemplified by the representation of a line segment by overlapping points (Section.4 in[1]). Here, an episode merely refers to a sequence of events temporally bound together, without any reference to an external source of timekeeping [51].

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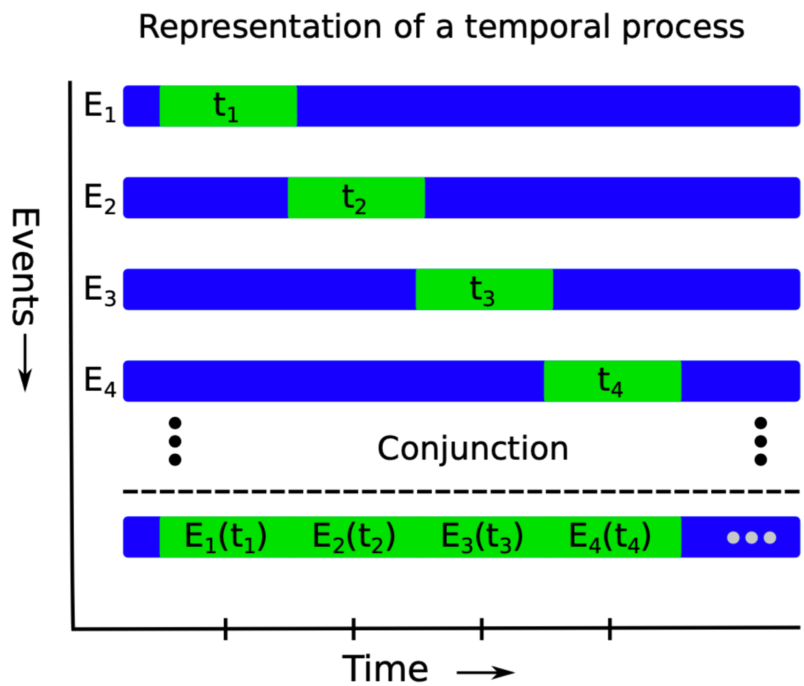

Figure 6. Graphical illustration of representation of a temporal event. Events E_i occur in temporal sequence. A colored bar shows the limits of correlation in relative time space for respective events; the range in green represents positive correlation, while in blue, the negative correlation. The green ranges are marked with t_i that represent relative times with respect to the neighboring events. Conjunction of such $E_i(t_i)$ is represented by a bar below the dashed line. This bar expresses the whole episode, a specific conjunction of events at their respective relative times.

Systems that evolve with time or with reproducible generations under certain selection pressure must possess physical structure and specific function of action appropriate for the causal function in the environment as per the demands of selection. Such a system may have broadly three subsystems: sensing (observing), correlating + inference drawing, and action execution subsystems, even if not neatly divided with well-defined boundaries or interfaces, in addition to the subsystem that represents the evolved biases (goals). This can then evolve into a formalized and specialized information processing system with the ability to observe and represent the structure and function of the holding body in congruence with the causal function in the environment to select action. This may significantly improve sustenance[52]. As noted earlier, the selection of action may evolve to optimally satisfy the semantics of certain preferential biases.

A system capable of visual and tactile observation of its own physical extents (limbs of the holding body) in constant structural relation within limits of variation may construct a representation of the structure in

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hierarchy as suggested above. Similarly, the constancy of functional relations, such as relative movements of limbs and their causal consequence, allows the representation of the structure of functional relations among limbs. As noted above, the components and their inter-relations are integrated at each step in the hierarchy, extending to the multi-modal representation of a unified descriptor, U, as a class of all representable specific physical structure and function at the lower levels. Similarly, the objects not bearing a constant relation (i.e., not bound) to the unified object U may get classified in contrast to the class of objects associated with U. This is a class of external objects, E, in the context. In fact, for the integration of action and its effect, U and E may constitute a domain of all observable objects, O. Similarly, the semantics of temporal dynamics of motor functions bound to the unified object U having a causal effect in the context O form a class, say A. It is apparent that A is a class of actions, and it may connect where actions are relatable. Referable relations of correlation among U, O, A, and the changes C in the context O are representable as causal relations among U, O, A, and C as shown in Eqn.11 (context Eqn.7). Actions are representable first in the system as intended actions before translating to motor functions. The ability to represent the temporal dynamics may easily extend to intended actions with continued modifications.

$$\begin{aligned} &R_{UOA} : \{U, O\} \mapsto \{A\} \\ &R_{ref-UOA} : \{\{U, O\} \mapsto \{A\}\} \mapsto \{R_{UOA}\} \\ &R_{UOAC} : \{\{U, O\} \mapsto \{A\}\} \mapsto \{C\} \end{aligned} \tag{11}$$

R_{UOA} expresses a causal relation that maps instances of states of U and O to the instances of intended action A. Similarly, $R_{ref-UOA}$ is a referential mapping that shows how the relation R_{UOA} is referably represented as per Eqn.5. R_{UOAC} expresses a causal relation that maps a combination of the three classes to the class of changes C in the context O. We may ask, “What does a referable disjunction of instances (states) of the unified object U in conjunction with the instances of the class O as a causal precursor to the instances of class A, in turn resulting in the instances of change C in O, semantically correspond to?” One may recall that the perspective of observed objects is always centered on the constancy of the unified object U as shown in Fig.5. It is apparent that the causal and contextual distinctions among the classes semantically relate them in different contexts. For instance, instances of class U may relate or connect where the semantics of an observer and / or an actor is relevant, instances of O where the observed class is in context, and instances of A where the actions are relatable. Moreover, top-down functional relations (specification) from higher-level contexts[20] fixate the semantics of an observer and actor on U. The disjunction of instances in different classes forms their respective class descriptors, labeled here as U for observer, O for observed, A for action, and C for consequence, which may relate as referable elements in higher levels of semantic structure.

At this stage, we note that a system based on the organization discussed above, with a network of agents in modular hierarchy, bears mechanisms to model and construct a referable representation of arbitrary objects in

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relation to the object U, and their structural and functional inter-relations, as well as the causal relation between actions associated with U and their consequences. The function of such a system satisfies the first-order definition of consciousness. All objects of relevance for action, including the causal relations in the environment and between action and consequence, are mapped to the object U. A component of U refers to the structure and function of the system itself at a level of abstraction that semantically qualifies the system as an observer and actor of action. Yet, the qualification does not include the observer (knower) of being an observer. That is, the semantics of the observer-observed relation is not yet referably represented in the system and mapped to U as having a functional (causal) role in action, as shown in the next subsection. Such a system can make a selection of actions towards certain goals without the knowledge of being a selector, or an actor, or the possessor of goals. Such a system may even sequence the actions suitable for a stepwise approach without the knowledge of being a planner. Such a system may evade processes that are in opposition to the embedded goals – e.g., evading approaching objects with suitable movements taking into account the limits of its physical structure and function, without the knowledge of being a controller. Such a system is capable of learning and acquiring knowledge in each of the domains noted above without the knowledge of being a learner.

Indeed, it differs from a system like a thermostat in many ways that need no elaboration here. Such a system also differs from unicellular organisms at least in one respect. Unicellular organisms do not have states that represent the semantics of their own structure and function unified into one abstract notion, semantics of its relation with external systems as being embedded in the environment, semantics of a cause-effect relation between action and consequence positing it as an observer, actor, or selector of action, even though behaviorally, and from a third-person perspective within limited contexts, there may not be a discernible qualitative difference. Now, given the nature of evolution under selection pressure, it is reasonable to expect that the structured biases, goals, and abilities of action may evolve in line with the sustenance of the represented unified object. One of the purposes such goals may serve is that the action pathways may be selected based on the context of the system (organism) while the goals evolve at evolutionary time scales (of species). Moreover, in order for the dynamic development of action pathways, goals must be referable or observable.

4.3. Representing self-referential semantics of actor, observer, and controller

In a way, it is easy to infer that the mechanisms used so far to construct a system that performs actions based on observed context, including the unified system and evolved goals, extend in scope via yet higher-level organization to include the actor and observer functions of the unified system as part of the observed context itself to generate action. That is, at the next higher level of abstraction, an agency emerges, whose components include the causal functions of the observing, acting, and controlling self in relation to the environment and the

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goals; the causal functions include actions and their outcomes. In short, R_{UOA} and R_{UOAC} in Eqn.11 form parts of observed dynamics, which in turn form the causal factors for superseding action. We refer to this agency as r-self and examine how it satisfies the second-order definition of a self-aware system.

A clarification is needed here before proceeding. Commonly, we refer to a conscious agent as a subject in the act of experiencing or as an experiencer. In the text below, the agent is referred to as an object of representation. The subject matter of this article is to deal with the semantics as objects of discussion; therefore, it may lead to confusion as to whether a term is used to convey the linguistic meaning to a reader or to refer to the object represented by a state of the system. Therefore, a method is devised to indicate the correct identification of the meaning of a term where there is a possibility of confusion. A prefix, ‘r-’, is used to designate the terms that refer to the represented objects; ‘r-’ stands for ‘representation of’.

Here, we trace a path to construct semantics of self that includes being an observer of self, effector (actor) of change, comparator of the predicted outcome of intended action with the goals, hence, selector or controller of action. It is by no means an assertion that the mechanism presented here is in any way unique for creating a self-observing system, for the mechanism is generic to support a multitude of pathways to create the semantics of r-self; at best, it constitutes an instance of such a possibility.

In line with Eqn.11, we consider causal, referential, and compositional relations (mappings) that encapsulate the emergence of r-self.

$$\begin{aligned} &R_{UOAC}: \{U, O, A\} \mapsto \{C\} \\ &R_{ref-UOAC}: \{\{U, O, A\} \mapsto \{C\}\} \mapsto \{R_{UOAC}\} \\ &R_{comp-self}: \{U, R_{UOAC}\} \mapsto \{R_{self}\} \\ &R_{pred}: \{\{R_{self}, O\} \mapsto \{A\}\} \mapsto \{C_{pred}\} \\ &R_{result}: \{C_{pred}, O\} \mapsto \{O_{new}\} \\ &R_{diff}: \{O_{new}, \{Goals\}\} \mapsto \{O_{diff}\} \\ &R_{mod}: \{R_{self}, O_{diff}\} \mapsto \{A_{new}\} \end{aligned} \tag{12}$$

The above expressions are indicative or suggestive of the steps in the mapping of classes of objects. R_{UOAC} is a mapping from the three classes, U, O, A, to the class of C, representing a causal relation. This leads to a referential mapping $R_{ref-UOAC}$ to the relation R_{UOAC} that creates a reference to the semantics of U in the observed context O as a precursor to action A, which in turn forms a causal precursor to change C as stated above. A compositional mapping $R_{comp-self}$ is constituted of U and the relational mapping R_{UOAC}, that includes U in the reference to R_{UOAC}, and maps to the second order definition of R_{self} or r-self, a self-observing self. As we noted above, the right-hand side of a map forms a referable object. This r-self may be further enriched or related to other functions of self as discussed below. Thus, there exists a path to represent ‘r-self r-observing r-objects’, where the r-objects include the composite of U and R_{UOAC} or the observing and acting unified system. In a re-entrant system, such a referable representation of self may even be recursive, representing an r-self$_n$ that observes an observing and acting r-self$_{n-1}$ for as long as the layered observation of r-self remains relevant in the evolving context. Any expression based on this observation refers to r-self$_{n-1}$ as an observing and acting agency overriding the previous r-selves within a continued episode. That is, a report may include only a referable observed relation involving r-self in the previous iteration.

Similarly, when the class of action is conjugated with the observer class, the composite class may connect in contexts where the act of observing or making an observation is relevant. Similarly, the observer class may be conjugated with any sub-classes if relevant, for instance, with visual observation, a seer; with aural sounds, a listener; with tactile senses, a touch / pressure / heat sensing agent; with thought chains, a thinker; and so on. Each of these classes is referably representable. We ask, "What may the class of disjunction of a seer, a listener, a touch sensor, etc., of objects semantically correspond to?" It is apparent that such an emergent class as a referable object may relate well in contexts where the generic semantics of an experiencer, or the self in the act of experiencing, serves as an element. That is, the mapping of such sub-classes of semantics of agency to the object r-self serves as qualifier sub-classes of r-self as a unified agency. It is apparent that the process of constructing an experiencer sub-class is not limited only to the three domains of senses but applies to all that can be classified under classes of observed or sensed, such as goals, wants, thoughts, actions to match goals, or any other referable objects. It is instructive to label such classes of agency in linguistic terms to understand the variety of abstract qualifiers we use to qualify ourselves.

The steps suggested above may be realized in the following manner. From repeated observations of causal correlation between elemental actions and their internal and external consequences, a map for this relation may emerge under a population coding scheme, as discussed above, for its relevancy[53]. It is possible then that the specifics of an action and its result in the observed context are communicated to modules that relate to r-self before it is acted upon (see maps $R_{ref-UOAC}$, $R_{comp-self}$, and R_{pred} in Eqn.12). With respect to r-self, the referable class of such actions bears a semantics of intended actions, which, when applied to the current context O, yields a new context O_{new}. It then becomes possible to relate the result of the intended action, O_{new}, to expected outcomes or r-wants (map R_{diff}). The choices of action become competitively selectable based on the alignment of O_{diff} with the optimal realization of the active r-wants by the same process of competitive dominance of coherence. The classes of intended actions, their outcomes, and comparator relations are referably representable via mapping for their relevance in the selection of action. Again, a conjunction of r-actor with context-specific selection of action creates an r-selector class, another sub-class of r-self. Moreover, since the system described here has the ability to select an action and predict the consequence, it can be applied in a series of steps with evolving outcomes to represent the temporal process as a whole and to evaluate the comparator function at each step with r-wants. Furthermore, by tracing such paths repeatedly in different contexts, a store of useful elemental paths may emerge for different classes of elemental contexts in different modules, which may then be competitively traced in parallel, discovering paths for a structured problem, corresponding to a plan. A few of them may even be acted upon simultaneously, as we observe from our behavior. Parallel evaluation does not necessarily relate to r-self at each step, remaining subliminal. Moreover, trial and error and observing other systems carrying out a task at a conscious level may help organize a sequence of actions towards specific goals.

The mechanism places no limits on how many competing considerations may participate with differing relative weights of satisfaction of goals in the selection of an action; the limit arises from the sharing of resources. All of these processes form elements of observed context that map to r-self, creating referable semantics of selector of actions, controller, or decision maker. Moreover, if a system develops a representation of a pseudo-random selection of action that may satisfy certain goals, then that may also constitute one of the competing r-wants in determining the action. Therefore, the 'freedom of will'[54][55] is a representation of an abstraction of observed phenomena of evaluation of selection based on the consequence of r-choices satisfying r-wants related to r-self. Once this abstraction of freedom of selection is referably represented, it can also become one of the overriding r-wants in selection. 'Freedom of selection' manifests less at the moment of activation (evaluation) of wants against options, but more in the formation of such competing wants. The wants may undergo a non-linear evolution via extended context of their realization, or lack of it, in accordance with the requirements of more basic emotions within an evolved limitation of diminishing returns and their inherent incompatibility to avoid run-away processes. The fuzzy terms 'less' and 'more' are used to take into account a limit of randomness in neural function and non-linear dynamic evolution. It may be noted that if a specific selection is a deterministic outcome of the prior state at all times, then 'free will' is a notional representation, but if it does not depend on the prior state at all, then it is random. Due to an inherent limit in randomness, an outcome of limited indeterminism[1], and non-linear evolution of wants, the reality is in between the two, making the 'freedom of selection' a relevant semantic value.

In an extended temporal event, r-wants causally affect the decisions and actions towards specific r-goals as observed by r-self over the duration. But to report on a decision to act at a sharply defined moment (say, on observation of a stimulus), a referable memory of the selection must form, then the report constructed referring to the selection as in the present, resulting in a short time lag between the two. The point is that the context-based decision to act by the agency of r-self must be related to or mapped to the next iteration (level) of r-self as having been observed to have a causal effect of the conscious act. In fact, a system can report an event only when a memory is formed, where the tense of the report is expressed by the temporal semantic value represented, not what an external device can determine (see[56][57]). Soon after, when the time lapse is represented, the report may refer to the past. A real-time system developer knows well that even while reading, evaluating, and recording the time of an event (say, a GPS signal), the time is elapsing, which must be modeled.

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Even in the brain, a perception (report) of simultaneity is created between visual and aural receptions of an event tens of milliseconds apart.

In summary, we may note that any such endeavor that aims to describe the minimalist central mechanism of emergence of the semantics of r-self as an r-observer, r-actor, r-experiencer, and r-controller cannot be particular to a specific real system; however, the mechanics presented here are observable in such systems. The human brain has evolved an extremely rich set of semantic values that relate to the identity of r-self, e.g., specifics of senses, thoughts, memories, relations, knowledge, memes, values, desires, abilities, and so on, all by the same mechanics presented here. This work does not attempt to identify human brain areas that may represent different classes of objects discussed here.

Thus, it is concluded that the semantics of 'r-self r-experiencing r-object', or 'r-self r-controlling r-action', are entirely constructible with any contextually required level of specification, structure, and abstraction. Here, r-experience is the semantic value that qualifies what the experience is to the r-self, or r-self's relation to r-object as a part of R_{UOAC}. For instance, r-experience may include the semantics of reference to r-object, or action by r-self upon r-object, and so on. To emphasize, when one refers to oneself as the experiencer subject in a thought, that subject is the object r-self in the semantic representation of the thought. The abstraction of consciousness then becomes a referable semantics of r-self's relation R with r-objects having a causal effect as in the definition proposed; consciousness is a perspective from the viewpoint of an observer r-self at a subsequent iteration in a re-entrant processing as shown in Eqn.12. This further provides a robust rationality as to why consciousness ought to be subjective. It is of particular importance to note that if an object is represented in a system but does not relate to the r-self, then the r-object does not form a part of the relatable conscious event. That is, an experience is necessarily relative to an experiencing agency.

In general, the objects of representation have a lifetime for as long as the states of agents are preserved; the transient nature of active states of neurons makes the objects of experience transient too. However, the re-entrant activation in a loop preserves the continued semantics of objects, where the active state of an agent represents the continued process or the relevant historical perspective. Since the idea of controlling action and temporal processing of causally connected events is to sustain the experience in the present even during the recall of memories, the objects of experience ought to be transient. Moreover, the function of consciousness is inextricably linked with the function of action, internal (as a generator of a thought chain) or external (brain, body, environment), which can be continuously generated even for no action; transience is a norm.

4.4. The control of action, central to the emergence of consciousness

First, consciousness requires the representation of a semantic structure that includes the self and its relation with the objects. As we noted, it requires deeper levels of abstraction from the primitive sensory information.

Such an organized system is unlikely to come into existence by random processes alone without the mechanism of selection requiring the evolution of modeling and acting subsystems to meet the varying requirements.

The complexity of the organization of systems evolving over generations or over the lifetimes of their function, with the ability to adapt to the dynamical environmental contexts for their sustenance, is markedly different from those that arise from a large number of elemental parts forming a complex pattern, function, and structure under certain rules or relations[58][59][60]. While the evolved organization of the former acquires functions to meet certain specific purposes even in dynamically changing contexts, including those that have never been encountered before, the latter does not. While the former may not emerge spontaneously as the path of evolution is based on variable external selection, the latter may. Therefore, the former must possess a capacity to self-reorganize in order to model (learn) the dynamically evolving context to control or select appropriate action to meet the evolved goals and to enhance sustenance. Different subsystems that sustain the internal environment in a relatively stable (constant) state within limits, such as homeostasis, may evolve to be autonomous, but the same is not true for external contexts, which cannot be comprehensively controlled. Therefore, a highly evolved system like the human brain must be able to select and follow a coherent action, avoiding different subsystems functioning at cross purposes detrimental to the very sustenance of the system as a whole[61]. The creation of a singular abstract notion of self enables an evolutionary process to support function and organization with a single objective to optimize, enhance, and preserve the unified r-self that includes critical features of body and mind, rather than conflicting multiples. Even for multi-headed systems, a protocol of messaging must exist to decide precedence, which effectively amounts to a unified system. The corpus callosum in the human brain also seems to perform the same function. Hence, an organism's sustenance may critically depend on a centralized system of decision-making with overriding control. Such a need leads to a representation of a unified self, to which all wants, desires, and contextual details are mapped for the evaluation and selection of a suitable course of action for the sustenance of self. In addition, with the abilities to follow different action pathways internally, as part of a selection of the most dominant coherence, satisfying optimally the r-wants associated with the r-self, the abstraction of 'self as a controller of action' emerges.

In a modular system, the components of r-self are distributed among different functional spaces. It is indeed likely that actions, even in minimal (first-order) consciousness, may arise from any of these components, and only in cases requiring a wider scope of relations, comparisons, analysis, planning, thoughts, etc., does the higher-level self-referential r-self act like a controller. If the r-self is the sole agency in control of the system for action, then only those r-objects that relate to the unified r-self may constitute parts of a reportable or actionable conscious event. When a conscious system refers to itself in a physical expression (verbal or otherwise), only the r-self in control of the physical system can do that. It may be noted that the active state of a

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neuron intrinsically may correlate with extended information as per the law rather than just the relation of self with the objects, but they do not form parts of conscious experience. The conjunction of a population restricts the information to the semantic value of the relation the r-self has with r-objects, which map to a population in another module for action. Therefore, in order for the semantics of a specific relation of r-self to have a definite causal influence, a single neuron can rarely be the cause of an action.

In fact, a system may even construct representations of other agents, their functional relation with objects, their goals, their actions, and outcomes, which may or may not relate to r-self at a given moment to form a part of a conscious event. Objective functions of r-self may also form associations with other agents (recall mirror neurons[62][63]), but such r-agents are rarely mapped (with probable exceptions such as hypnosis) to bear the r-controller element of the unified system. Thus, functionally represented semantics of a 'unified system as an observer and controller of body, action, and thoughts' serve as an all-encompassing conscious agency in all references to the self.

5. Interpretation and conclusion

For the first time, a framework for the emergence of consciousness is constructed with semantics of information of causal correlation of the state of physical systems, leaving no insurmountable conceptual gaps and voids. A reference to the semantics of 'unified system' functions as an abstract identity for the self in a context. This does not lead to infinite recursion, for a reference to the product of disjunction is not reducible to an instance in every context, whereas a bottom-up construct relates the self in a limited domain. Given the quantitative methods of information processing and construction of structured and abstract semantics, dynamically evolving artificial systems are constructible without limitation.

5.1. The critical role of language

The role of language in the emergence of consciousness is deliberately left out of consideration while dealing with the mechanics of emergence of self and its relation with the rest, for language also emerges in the same process. That is, language does not form the basis of the emergence of consciousness, even though language plays a critical role in advancing the abilities to construct higher-order abstract semantics in general and self-awareness in particular[64].

As we noted above, a semantic value becomes accessible when active states represent the value in a context where it relates well and stays relevant. That is, beyond a degree of limited fluctuations, there is no mechanism for accessing a semantic value without the presence of a relevant context. But we also noted that the active state of groups of agents in a module represents specific values, which may arbitrarily connect to other modules that are coherently active based on relevance or proximity in any parametric space, forming significant correlations

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(e.g., Gestalt principles). A modular structure covering the space of verbal or visual symbolic expressions may evolve connections with arbitrary modules in the system bearing repeatable association. That is, it is possible to associate or relate arbitrary semantic spaces by virtue of their co-activation or by any other mechanisms that the mapping system uses to create connections. Therefore, specific graphic symbols (graphemes) and the aural or visual forms/terms may be arbitrarily connected to referable semantic values if such terms and forms are co-activated during accesses to such values. In fact, such an association of terms with semantics is natural to expect if all semantics/objects are constructed of relations, where relations can be arbitrarily set. As discussed in Section.8.4 of [1], linguistic terms and forms are constructible along with their syntactical schema with pre-assigned semantics, where an expression with such terms is evaluated in terms of disjunction and conjunction of the semantics that the terms and forms refer to.

Armed with such an association of formal terms and expressions with referable semantics, it becomes possible to connect terms with r-self, r-experience, r-action, r-causation, r-object along with their functional variations to be able to express, 'I see the blue sky'. The commonality of functional variations in r-objects enables common linguistic variations (syntactical forms) to emerge in respective terms for objects (nouns), actions (verbs), relations (prepositions), qualifications (adjectives), etc. Moreover, the terms having definite context-dependent specific relations with other terms, when used within a linguistic structure, limit the expressed semantics with far greater specificity and concreteness than the fuzzy semantics of active relations with a multitude of wide-ranged correlations. Furthermore, by mere expression of terms in a certain order or proximity as per the semantics of syntactical forms / structure, it becomes possible to combine or relate semantic values in ways that have never been related / mapped naturally in the contexts encountered by a system. For this reason, the learning and communicating potentials become unlimited. For instance, the term 'right angle' may have been initially associated with a relation between two lines, but now linguistically, they can be used to relate two vectors or planes, further helping to create the semantics of orthogonality. If one organism of a species with a common brain structure expresses a certain semantic structure with such terms, then the referenced structure readily gets communicated to other organisms within the limits of variations in semantics associated with the terms. Such expressions may even be recorded in a medium and re-accessed in arbitrary forms, providing continuity of concepts to future generations. For systems without such modules for symbolic mapping to represent higher-level abstract semantics, it must evolve modules that represent the specific relations expressing the semantics.

Given the mechanism of integration at each step in the hierarchy and back propagation to the specifics in respective modules, a new concept expressing a relation may get represented by the connections within the modular hierarchy of language rather than among the r-objects in different modules, such that an activation of a relation among the terms within the linguistic structure activates the referenced semantics in different

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modules. While most linguistic expressions are instances of this phenomenon, consider an extreme example, "X hammered her idea into Y's head!". We may have a specific semantic representation of the object hammer, the repeated action of hammering, and the class of physical objects that are usual targets of the action. In this expression, a non-physical class object (idea) substitutes a class of physical targets, and head substitutes the brain, which in turn is a substitute for the mind, yet we form a rather concrete semantics of the expression on its first encounter. A language provides a means to substitute objects with other objects where the homomorphism (analogy) between their respective structure or function bears relevance in the context.

Once a term, such as 'consciousness', is created to refer to the disjunction of instances of r-self's relation with r-objects, then such an abstract semantics may further relate with objects in relevant contexts. For example, expressions like, 'What is consciousness?', 'How am I conscious?', and, 'There is a hard problem of consciousness', become constructible. That is, with the advent and evolution of language, the term gets much sharper meaning and richness with a variety of connections due to the definite relations in which it can be conjugated with other semantics. It is apparent then that the diversity and specificity of the sense and awareness of consciousness may have evolved with the evolution of language[64].

5.2. Relative nature of representation

One of the important properties of such a representational system is that descriptions of all objects are only relational, including even those that are directly acquired from the external world, such as pixels, temporal variations of vibrations, pressure profiles in pixelized form, etc. Consider, for example, a two-dimensional pixelized array of a sensory organ, such as a retina. A specific configuration of on- or off-center[65] contrast relative regions (points) forming a line segment may be represented by a dynamical system of representation based on its statistical relevance. A point to note is that given a set of objects, what relation gets represented depends on its relevance; the mapping system shown in Fig.5 is independent of any particular relation.

Similarly, if the two-dimensional pixelized array is constituted of three types of light sensors, sensitive to different ranges of wavelengths, similar to the cone cells in the retina, then any arbitrary relation among these can be represented based on their relevance to the system's function. Since surfaces of physical objects exhibit constancy in their light reflectivity or transmission properties, it allows an observing system to represent such a relation. Moreover, lighting conditions, shades, depth or distance, motion, etc., do not change the reflectivity; the system would be able to construct a disjunctive mapping to represent the constancy of reflectivity of a surface under all variations observed. Naturally, such a mapping requires inter-dependent modules to represent objects (relations) in each of these domains. For evolving systems under selection pressure, the specific relations of contrast and similarities relevant for behavior are most likely the relations to find representation. Since the area of space is integral to the relation of reflectivity with the surrounding, it forms a structured relation as it further relates to r-self; hence, an area of space is an inseparable component of color perception. Moreover, since lighting conditions alter the measures of light in different wavelengths reaching the retina, the relation is not specific to particular wavelengths. In fact, different combinations of wavelengths in varying contexts map to the same class object, hence creating the same percept. Here, we noted the semantics of color perception of surfaces that relate to r-self, such as the blueness of the sky, not the semantics of blue. The same perception may have an association with a number of objects in different contexts, such as blue sky, blue wall, blue paper, blue reflection, etc. A referable abstract semantics may emerge from a disjunctive relation among such descriptions to label the reference as blue. In other words, the semantic relation of blueness is primary for the abstraction of blue. It is fallacious to trust that blue is an inherent property of physical objects in nature and then wonder how blueness may arise. It forms a conceptual error to look for the manifestation of blueness in the physical world other than in relation to r-self in the domain of representation. Blue as a label serves as an abstract qualifier to an object, but it does not cause a perception of blueness unless it is instantiated on a spatial extent of the object in a top-down activation, similar to the way a specific right angle may get instantiated in the context of a reference to 'right angle'.

Since all descriptions are built from relations, even the blueness of the sky, it is entirely possible to have the same vivid experience, even without the sky, if the retinal neurons, or the LGN neurons, or even the cortical neurons in the visual system of the brain are activated in a specific pattern. All the blueness and depth perception in relation to the r-self would reappear. A subjective dream event constitutes sufficient evidence of that. A sense perception in a phantom limb can only be a semantic attribution. That is, what the r-self is r-conscious of is not the quality of reality of the external world, but rather the relation constructed by the organization of the neural connectivity and the relation among the activation patterns of the neurons in that organization. The physical systems like the sky and other objects bearing constancy in their reflectivity or transmission simply enable the neural system to self-organize to represent the relation. The sensory neurons serve to keep the relations in conformance with the behaviorally useful relations in the external world. When a system predicts and takes appropriate action, the system observes conformed results, which are used to reinforce the mechanism of prediction[66][67][68].

5.3. Comparison with a bat's system

The projection network of modules determines what structure and abstraction the recipient modules may represent via conjunction and disjunction. Given the stark difference between the sensory systems and the projection network of modules in a bat's brain and the human brain, the abstractions of irreducible emergent semantics between the systems are not comparable, which creates a non-bridgeable gap in the subjective r-experiences of the r-selves of the two systems. The represented self in the human brain has no mechanism to relate with the abstractions represented in a bat's brain[69]. This provides a natural explanation for the incompatibility of subjective experiences represented by two species, even though the mechanism of forming such experiences is objectively common. That is, the mechanism of emergence of consciousness is such that it limits a conscious agency to a set of specific abstractions, which undergo continuous change with every experience. A subjective sense of empathy with other humans and the commonality of reporting the same are only possible due to near-identical modular projections in hierarchy, resulting in very closely related abstractions of the semantics of objects and terms. This inference of continuous proximity relation stands against the idea of the Inverted Spectrum[70].

5.4. Attention and its role in differentiated action

The mechanics of top-down mapping at each step in the hierarchy that provides more global context to each module, allowing them to select more relevant processing, suggests the mechanism of attention rather naturally. At any given moment, a large number of elemental processes take place within the physical brain, but the ones that integrate through the hierarchy and relate with the r-self, having stronger relevance in the context, are back-referable via top-down mapping[71][72]. As shown in Eqn.3 and in Fig.4, the same expression serves both ways in the construction of semantic values. Therefore, the formation of a high-level context relating to r-self, in conjunction with the specific r-goals or r-wants of the moment, enhances the relevance of certain r-objects distributed over the object spaces. The top-down propagation of relevance strengthens the competitive edge for such r-objects at respective modules, enabling enhanced specification via greater synchronization, larger conjunction of elements, and recurrent looping. This enhanced specification integrates bottom-up through the hierarchy to form a part of a new context relating to r-self, enabling much sharper specification for further processing or action. This top-down and bottom-up process of enhancement of specification for certain r-objects functionally defines attention. Unless the specification relates back to r-self, it could not form a part of consciousness. Second, in line with the emergence of the semantics of the actor element, the causal dependence of enhancement of r-objects on r-wants associated with r-self creates the semantics of r-self being the director of attention. Third, the same top-down process of referencing holds the potential to create mental imagery[73] with vivid low-level specifics when bottom-up processes from sensory modules are absent or overridden.

There is yet another primary function of mental attention that requires our attention. At top-level modules that represent integrated classes of r-self, each agent (neuron) projecting to motor areas represents a highly integrated context, which does not provide differentiated detail for specific action. Therefore, it is expected that the attended r-objects in different modules must also map to the motor areas to make object-specific

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differentiated details available for precision control of action in accord with the attended r-goals at high-level integration. This is empirically verifiable.

5.5. Active vs. passive representation of functional objects

The active states of neurons have real-time direct causal consequences in the network; therefore, they constitute an instance of active representation. Memories form via active connections and their strengths, forming associative mapping with related objects. When reactivated, the associative relations to objects turn active, functionally serving as memory recall. That is, all three elements of processing, namely, the object specification, the memory, and the action as per the function of the object, are inbuilt into the neural process. This is unlike the von Neumann architecture, where an independent processor fetches instructions and coded memories from passive addressable storage and carries out the instructed function without any regard to the semantics of the coded information – an instance of passive processing. This necessarily requires interpretation of the resultant states / values. The neural activation pattern carries out the function of the objects within the domain of representation via causal correlation. It is possible because the function of objects is specifiable by a uniform expression in terms of conjunction and disjunction operators, which is also the mechanism by which the neurons carry out processing via coherent activation. Therefore, objects with arbitrary functions may be created in the domain of representation without any correspondence in the physical world. Moreover, the representation can be dynamic because a neural state only represents the semantics expressed by the said expression on the values represented by the active presynaptic neurons. Furthermore, the connectivity with other neurons and their weights may change gradually with time, changing the semantic space represented without resetting the system. Such a system can have a dynamic control over the external world.

5.6. The power of associative recall of contextual elements

One of the most powerful consequences of associative recall by active agents in a population-coded system is that a related context is made available that helps comprehend the current observation or interaction with the environment. At any given moment, a system observes a limited set of elements in a context, but the ability to access elementally associated information at all levels in the hierarchy[74] to carry out competitive coherence over all accessed space creates a suitable convergence of applicable context. For instance, in the ionization chamber experiment, as shown in Fig.3 of[1], the current generated by the coherent convergence of electrons on the anode is observed by the experimenter. But the recall of the spatial isolation of the chamber, the electric field, and the models of ejection of electrons from argon atoms by a heavy ion process enables the associative brain processes to immediately relate the measure of current above the threshold to a heavy ion process.

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Without such an associative recall to a list of relations, a physical system must observe specific causal correlations with each of these semantics at once to form a conjunctive relation among them to correlate with the heavy ion process. An organism's survival and performance critically depend on the power of such associative recalls. In fact, associative mapping based on limited observation of relations is also the cause of so-called intuition in our thoughts [1]. That is, intuitions are not a product of formal logic. The leaps in interpretations are also the cause of most perceptual illusions[75][76].

5.7. Consciousness vis-a-vis causal powers

This work shows how the causal function of a physical substrate and experiential content are inextricably connected. It offers an explanation of why and how an experiential state can have a physical consequence (also see[70][77][78][79][80]). As part of the integrated semantics, the r-self relates to r-objects as an agency with motive and causal power to effect change. The semantics of experience attributed to the r-self is a part of the causal correlation of a coherent state of a group of neurons resulting from processing organized in a modular hierarchy. So, does the represented semantics of willfulness to act have causal power? Naturally, yes, as it requires the group of neurons to functionally connect in a specific relational structure to effect a definite coherent state among the recipient neurons in order to correlate with the causal consequence of the function of willfulness to act, as we also observe in our thoughts. Without the causal correlation with willfulness to act, there cannot exist the specific coherence of states in exactly the same context to have the same causal effect. In other words, a representation of semantics emerging from causal relations cannot be separated from its causal function. Any statement to the contrary is in logical and natural contradiction to existential reality. Therefore, every semantic value represented in a system, conscious (relating to the r-self) or otherwise, has causal function; some may even have a function to negate others.

Information of causal correlation has an existential reality in the natural universe, but information is not directly observable with a probe. Moreover, since information arises from the constancy of causal function in nature, there is no existential reality of information that is not a part of the causal correlate of a physical state. Every bit of information that we construe, including the ones that we attribute to other systems as having, such as a DNA strand, is constructed in the brain based on such causal correlation as presented in part (ii) of the law. Due to the function of disjunction in causal correlation, the objects referred to by information may not have an external existential reality, but the information itself remains undeniable. Information serves as a medium to all knowability, whereas information itself does not require any medium, i.e., this is the only reality of nature that we have direct access to in a definite sense; all other descriptions of natural phenomena remain subject to interpretation, hence subject to change with time! With the advancement of knowledge, notions of charge, mass, and fields may transition into different objective models, but the information of correlation, hence the

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represented perceptions of the moment, remain unmodifiable, non-revisitable, even though memories can be modified. As also asserted in[1], time reversal has no basis in reality. The reality of perception is in direct contrast to what several authors call illusion[52][81][82][83]. Whether it is an illusion about the mind or about the external world[83], either way it is constructed of semantic values. If one takes illusion to mean a false perception, then perception is still there. Besides, (nearly) all objects of perception are non-physical. Consider a specific book in the field of view that one has a perception about. A range of values in nearly all apparent features of the book, such as shape, size, color, texture, relative dynamics, etc., are non-differentiable. Hence, the perception encompasses a class of indistinguishable variations, which is not the reality of the given book. Therefore, one's perception of the specific book is an illusion. In fact, this is coded in the statement of the law itself, which expresses the causal correlate in terms of a disjunction of conjunctions of states.

Following the natural causal relations, that which needs no interpretation, if an autonomously evolved system, such as a human, expresses a reference to itself, it must certainly have a causal representation of the self and the objects that it relates to. A reference to causally represented semantics of self unambiguously establishes the existential reality of the referrer self – 'I think, therefore I am' has a robust basis, causally so well founded that even a well-represented assertion, 'I do not exist', cannot falsify the existence. Similarly, the represented semantics of the referrer as the referent establishes self-aware consciousness of the second order. This conclusion stands against the very idea of zombiehood [84].

The mechanics presented here deviate from established processing schemes where a resultant state at each step is arrived at by a conjunctive mapping (think of a one-to-one function), which continues to bear dependence on the coded objects. The result may only be interpreted by an external agent with the scheme of coding and specific processing (mapping) as indicated by John Searle[85][86], who holds that any processing based on syntactical rules cannot ever capture the meaning (semantic values) necessary for a conscious system. But if the causal function in the rules allows for disjunction of arbitrary conjunctions, where specific conjunctions hold instances of a relation covering the space, then the disjunction represents the relation as a class object without a dependence on the underlying objects, as discussed in Section.3. Meaning still emerges. Arbitrarily assigned values are absolutes, require interpretation, a frame of reference, but relations do not. Searle's arguments fail to encompass the mechanism of emergence. An artificial system too may self-organize, as detailed above, under a devised causal scheme and arbitrarily set biases (goals); the representation of self may emerge from the observations of self as an actor, as an observer (experiencer), and as a controller to have causal function within the realm of the devised scheme. But if the system is required to have a function in the natural world of time, space, and other causal functions, then the emerging r-self is also bounded by the same constraints of the natural world. Since all causal functions are expressible in terms of conjunction and disjunction and organized in a population-coded modular hierarchy, there is no particular dependence on biological systems (in contrast to[87]).

5.8. Blueness of the sky and the light of consciousness

We consider here a few common fallacies to compare and contrast with the emergence of consciousness from causal information (ECCI). In our articulations, we often tend to place the experiencing entity and the objects experienced into two distinct categories. The experiencing self is taken as putative, and we seek to discover the reality of qualitative or 'phenomenal' experience in nature, either in the form of qualia or corporal senses, which immediately runs into a problem with the existing scientific knowledge and the closure of causal function. One tends to hypothesize new laws that directly or indirectly include such senses. ECCI stands in contrast to such ideas by virtue of the intrinsic causal correlation of a state with semantic values and the quantitative foundation to evaluate and build semantic structure represented by the active state of neurons bridging the explanatory gap[88]. It also provides an objective causal basis to subjective consciousness, enabling the implementation of such systems.

Color perception, such as blueness, is often cited [13] as a qualitative character to emphasize category difference from objective reality. It is noted above that the character of blueness is an abstract semantics in relation to 'r-self as observer' emerging via a disjunction of relations, such as contrast relations in shading, lighting, reflectance, or transmission of light in different wavelengths, etc., spread over an area of space, in addition to functional relations with other objects. It is not reducible to a specific conjunction of physically manifestable objects except the part of space. The question is, "How should this abstract semantic value relate to observer r-self such that a response based on this value conforms to external context?" First, it is no different than asking the question, "How should an abstract notion of 'right angle' feel?" Second, via top-down mapping, the structure of contrast relations spread over an area is referable and paid attention to. Third, in different contexts, experiences of blueness may get associated with certain abstractions such as likes and dislikes, or states of emotion; therefore, the perception of blueness includes a functional relation with such abstract objects and states. Fourth, the paradigm of population coding readily suggests why different contrast relations can be judged as close or distant with arbitrary precision. Fifth, it is possible to construct expressions within the framework of a language that requires a response in terms that is not satisfiable (see Russell Paradox[89]). For example, 'what it is like to be experiencing blue?', formed as a query, can be satisfied either by accepting its irreducibility without objectivity or by providing a communicable reductive description enabling one to evaluate how it should or should not feel; either way, it excludes an objective account of subjectivity as shown here. Only for the reason of creating an instance of a right angle in terms of two visible specific lines does one develop a sense of satisfaction as if one has a description to know how the relation feels. When it comes to communicating the same, one merely draws multiple instances of a right angle in relation to acute and obtuse angles and relies on the ability of the observer to form a referable irreducible semantics of a right angle via disjunction. But when the level of abstraction becomes deep and multi-dimensional, where components themselves are constituted of abstract elements without any physically manifestable instances, it creates a gap in communication. The question is not why the blueness feels or relates to r-self the way it does; the right way to express the reference to the relation the observer r-self has with the specific class of irreducible conjugation of conditions of lighting, reflectance, area of space, and abstract liking, is that we have come to refer to the relation as the 'feel of blue' or blueness.

Recognition of first-person subjective experience as qualitatively different in category from third-person informational data in the physical sciences led some[84] to propose the quale as a primitive of subjective sensory datum. One asks[84] – why cannot the information processing be non-conscious, or in the dark and in silence? Though the question is metaphorical with respect to the light of consciousness, it directly manifests in our perceptions of seeing light and hearing sounds. A short answer is that the information processing is indeed taking place in the 'darkness of neural senses'; neurons and the brain neither sense nor are aware of the information, but the value represented by their states happens to express the semantics of a $4.\pi$ steradian (sr) space extending in depth around the r-self, where the points, lines, curves, shapes, and surfaces over $4.\pi$ sr bear specific mutual relations and with the r-self. Such descriptions may also include brightness, color, temporal dynamics, etc. For a moving observer, the r-self is always posited at the point of the observer, as shown in Fig.5, enabling the semantics of perception of unification. The embedding of the r-self in the r-context bears a causal function, which in turn is represented by active states of neurons in a network resulting in action. Similarly, the information happens to express the semantics of certain disturbance in a temporally continuous signal space embedded in the same $4.\pi$ sr space around the r-self. That is, a structured information is represented by the neural state that expresses the semantics of an r-observer r-observing the r-lights and r-sounds and r-causing an r-action. In this representation, the integrated component, r-observer + r-actor, stands for a conscious agency.

In fact, extending the metaphor to the physical domain, it can be asserted that there is no light and sound in the space around, but the semantics represented by the neural state objectify a self and the illumination in a 3-D space, where the objects are constructed from the physical function of electromagnetic and acoustic disturbances as reflected from the objects. Consider entering into an optically dark space (room), which has objects in space radiating and reflecting in microwaves or x-rays. That is, even for the r-self bearing the 'light of consciousness', there is no light and sound in the environment if it is not represented and related to the r-self. But by virtue of having the semantic representation of lights and sounds, the r-self may relate to them, where the structured semantics of this relation expresses the system being the seer of darkness and the hearer of silence. Such a representation does not require an actual space, objects, lights, and sounds, only the specific relations in a modular hierarchy, as is evident from dream events, but the relations (models) are constructed from the interactions of sensory systems with the physical environment around. The way color is considered synthetic, so are the senses of space, time, and physical objects; they just happen to bear a degree of consistency in the system's interaction with them as much as the color over an area does.

Alternative thought experiment to Mary's color vision[90]: Consider a person who has fully developed color vision, but by some accident or disease, she loses all color-sensitive cone cells, leaving only the rod cells intact, a variant of achromatopsia post brain development. In each of the visual experiments, she is unable to report color but reports only the shades of gray, similar to the way Knut Nordby reports[91]. But the connections in the visual areas of color processing are intact. When asked if she can see colors in her dreams, she may report affirmatively. Inheriting this cortical organization but without the cone cells in the retina, Mary may know the feel of colors without ever observing them.

5.9. Who or what is a conscious agent?

If we ask this question on a conceptual level, seeking to identify a physical system as a possessor of 'phenomenal qualities' of consciousness, we face an immediate difficulty. The difficulty arises from multiple perspectives. First, causal function in nature does not include the reality of phenomenal quale or corporal senses. Second, even from the natural information processing point of view, a represented semantics does not entail any conscious perception. Instead, a part of the structured information arising from second-order causal dependence carries the semantics of the self as the bearer of the characteristic qualities that we have come to associate with consciousness. That is, there is a reference to an object within the semantic structure, which includes a persistent dynamic model of the body as the bearer of the senses and the experiencer and controller of actions. The semantic structure entails a perspective that is always centered at this object (as in Fig.5), forming an identity between the body, the experiences, the memories, and the control of action.

It implies that even the perception of color, taste, smell, pain, pleasure, and emotions are constructed semantic values in relation to the constructed self having causal function as shown above. That is, the semantics of perceptions are inextricably bound to that of the perceiver. It may be noted that the question, "How is the computed semantics accompanied by a conscious sense?", creates a blind spot for thinkers from examining how the reality of structured semantics itself expresses the semantics of self as undergoing the semantics of senses. One must not lose sight of the facts that semantics arise from natural causal correlation, semantics capture the qualitative character as well, and the semantics of senses is a perspective from the semantics of self. Third, semantics arising from causal correlation is associated with a state of a system rather than with the system itself, and a system's state has a definite functional reality upon observation, for the qualities observed depend on what the observing system is sensitive to. Though the active state of a neuron is uniquely discrete, yet the information is not attributable to the neuron itself, for its function is limited to the time of activity. Every time a neuron loses its active state, it loses its association with exclusive semantic value, yet we continue to relate the identity of the neuron as before. There is no surprise then that during sleep or anesthesia, consciousness ceases, even though the system remains the same. Hence, a physical system cannot be said to be conscious in a fundamental sense of the causal function. It is worthy of recall that, as observed in phantom limb experiments[92][93], the semantics of senses are attributed even to the missing limbs or to the out-of-body images[94]. Therefore, one may continue to express, "I am conscious," but the correctness of the expression lies in the understanding that this attribution to the 'self' is a semantic value of correlation of a definite state of a group of neurons causally in control of action at the moment. The integrated identity among the unified system and the observer, actor, and controller elements is observed as a datum leading to the abstraction of causal inference (Eqn.7) of ownership of the senses and consciousness by the unified system. Yet such unification is seen divided in pathological conditions, where the constructed self disowns parts or the whole of the unified system[95].

5.10. The observables

Every mechanism, process, and feature discussed in the text towards ECCI construes a prediction, and where the correspondence is already observed in real systems, an explanation. Since this work deals with the fundamental basis of the reality of information, and the hallmark of brain function is information processing, it must set the basis to determine the physiology and function of neurons and their organization.

By virtue of being intrinsic, the information of causal correlation of an observable state cannot be measured with a device, though the correlates of states of neurons can be observed; the real challenge lies in the large number of neurons involved in population coding and in the dynamic change in their correlation profile. Three basic mechanisms, namely, 1. information processing via conjunction and disjunction, 2. re-entrant coherence building to capture constancy of competitively dominant relations, and 3. population coding, function together to dynamically represent the context. Each of these can be empirically tested as sufficient quantitative specificity is presented here. A correlation may also be tested for a negative range of semantics. Modular and hierarchical organization is now well established already. All neurons are capable of implementing the first mechanism, but the other two are a product of network function. For instance, if several objects in a field of view have the same rate of linear or angular displacement, the projection from active neurons representing the respective objects in motion will cause the build-up of coherence among the recipient neurons via a feedforward mechanism, resulting in the binding of the objects via conjunction. Hence, the active coherence among the recipient neurons must correlate with each element in the constancy of relation, but not with others.

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Moreover, it is likely that the neurons in the mammalian cortical layer-IV largely capture conjunction among projecting neurons to represent the composition of features, and layer-III their disjunction (the variation in composition). If so, then as the represented objects / features in projecting modules undergo change, the coherent population by frequency and phase in layer-IV may shift. But if the structure is kept fixed, the population in layer-III may remain stable. For instance, line segments may change in orientation, but the relation is kept fixed at a right angle. And when this relation is also dynamically changed, the population shift should be observed in layer-III. The top-down projection via layer-I may also modulate layers II and III in the same way, but by keeping the overall context reasonably unchanged, one may observe the said effect.

Given the detailed specification of the mechanics of processing, many different functional properties can be identified for observation. Of course, the simplest test is to simulate the mechanisms on artificial devices, then compute as well as observe the correlation. In fact, this mechanism of computing the values can also be used at sensory interfaces where the local mapping and temporal signals of the first sensory neurons are known, e.g., the response function of cells in the retina. The technique is also applicable to deep learning systems, enabling the evaluation of values of correlation of intermediate nodes.

Now, since all elements of consciousness are constructed of semantic values of information, Neural Correlates of Consciousness (NCC)[96] come back into sharp focus in a different form. A correlate is not specific to neurons, but to information. Ingenious experiments may be devised to observe neural correlates of semantic values of 'an object' being the observer or referrer of the objects in a context, the sensor of the senses, the actor of the actions, or the controller of change, and so on. That is, one observes correlates of the relation R in the definition of consciousness and the term R_{UOAC} in Eqn.12. These correlates are not required to be exclusive, yet satisfy sufficiency. It can be further established that the references to the self in expressions by subjects correlate with 'the object' in consideration as per the second-order definition of consciousness. In fact, observations of neural correlates of references to 'other subjects' (individuals)[97][98] in relation to their appearance, acts, motives, functions, causal powers, etc., constitute strong evidence for a similar correlation of an active population of neurons for the self. One may note, there is no perception without a mapped perceiver in the semantic structure, for a perception is only relative to the perceiver; a disjunction of relations to perceptions itself defines the perceiver. Also, the senses need to be attributed to a common object within a semantic structure for centralized control of behavior. Care must be exercised to ensure that the neural correlates are not interpreted based on any artificial causal constraints of processing in the system, which also eliminates any correlation based on assigned values. Most scientific experiments are analyzed based on interpreted causal constraints, making them a third-person perspective. This method of NCC differs from the so-called Turing Test[99], in that it is based on direct correlates rather than on the observed function or behavior of a system and their interpretation from a presumed causal basis.

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5.11. Consciousness vs. material existence

The intent here is to examine ontology vs. epistemology of existence in light of the finding that the apparent reality of consciousness is emergent from more basic causal information. We noted earlier that a correlation of an observable state with semantic value is based on the constancy of causal function in nature. Therefore, a causal correlation must naturally include the semantic value of whatever qualities of elements of reality are responsible for the change; a quality also includes the quantity. For instance, in the example discussed in the context of Eqn.1 and Fig.2, the correlation with 'mass state' encapsulates both the quality of whatever it is that we refer to as 'mass' and its relative quantity that caused a relative transition in the interacting system. Does this imply that the quality of mass is the most fundamental element in nature? Not necessarily. As noted in[1], an interaction proceeds over time and space, and the result of the interaction correlates with the coherent property that emerges from such an interaction. That is, 'mass' itself can be an emergent property observable (bearing a causal function) in nature. An emergent property is an abstraction of reality, such as momentum, energy, brightness, color, temperature, heat, etc. We know that the object observed is relative to the quality that an observing system responds to[1]. Without such an observation (interaction), there is no correlation with the respective qualities and their quantities. That is, an interaction leading to a specific observable transition in the observing system causes this quality and its measure to bear an existential reality to be referable. It is inferred then that all known or knowable objects have existential reality only in terms of the causal correlation of observable states.

This understanding provides a robust resolution to the age-old debate on what exists. As noted in[1], a decoherence completes the interaction, creating a record of the observed states and their correlation in turn. Given the reality of limited indeterminism[1], once a relative state description has resulted in an observed consequence, it cannot be undone from the perspective of the totality of the state of the universe. That is, the ontology of an object is dependent on the causal correlation. Since all our notable observations entail consciousness, some may hold a view that consciousness is the basis of all existence, but that limits the semantics of correlation relative to an observing self. The information of correlation may not create a physical substratum (see also[100]), but it projects the causal relation in the underlying substratum into a knowable substance. This inference is consistent with the view that the ultimate substratum may only have relations as observables. If the epistemology is extended beyond the knowability by a conscious agency to the correlation of all observable states, then, in that limit, ontology and epistemology express the same notion.

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6. An Overarching Remark

In addition to laying down the basis and mechanism of the emergence of consciousness from causal information (ECCI), this work also provides a resolution to several outstanding fundamental problems related to information processing and consciousness. For instance, 1. the semantic content of information is grounded in natural causal function; 2. the mechanics of semantic processing directly applicable to neural systems and implementable on artificial devices is founded; 3. a principle based on the constancy of relations in an arbitrary space of semantics is introduced as a uniform mechanism to construct object description via structural and functional relations; 4. the mechanism of abstraction and emergence is computably formulated; 5. the specification of the process of integration and binding is laid down; 6. the population coding of semantic values is expressed quantitatively; 7. the objective basis of subjectivity is derived from causal correlation; 8. a definition of consciousness relating to causal function is proposed; 9. what constitutes a conscious agency is identified; 10. the mechanics of attention and freedom of will are presented in a new light; 11. the role of language in the acute sense of consciousness is re-examined; 12. the process of evolution via selection is identified as the sole causal function responsible for the emergence of consciousness in an otherwise value-absent (neutral) physical universe. In addition, this work deals with the directly accessible or knowable reality of nature, whereas all physically observable properties are subject to interpretation and modification. This work does not include, 1. the specific function and physiology of agents in a network; 2. the specification of networking; 3. the specification of competitive coherence; 4. the specifics of modular organization for a given species; 5. possible sources of instabilities in computing; 6. the analysis of complexity; 7. entropy and energy considerations of physical systems, and such.

This work makes use of certain self-evident first principles. Information as a causal correlate of a physical state is based on the constancy of causal dependence; the interpretation of the result of every experiment is evidence. Conjunction and disjunction function as generic operators enabling expressions of structured and abstract semantics. Abstraction via disjunction causes the emergence of classes and relations and enables a mechanism of referencing such objects. Moreover, since all specifications are based on relations, and a relation is uniformly expressible in terms of conjunction and disjunction, what physical entities and functions constitute the elements and mechanisms is immaterial. Similarly, the constancy principle is based on the fact that an object is referable only due to certain constancy in its structure and function, which forms a robust mechanism to construct its specification. The population coding method based on the constructor expression enables the process of competitive coherence building to capture relevant constancy in the observed context and to represent practically unlimited variations in object description. A re-entrant modular and hierarchical network is an organizational principle to allow constructing self-referential arbitrarily deep structure and abstraction.

The objectivity of the intrinsic correlation of a physically observable state to the information of its causal dependence, computable in terms of conjunction and disjunction, bridges the ‘explanatory gap’[88] between the objective reality of physical function and the subjective reality of consciousness. If the causal function in a universe has sufficient complexity to organize processing in a modular hierarchy, then the universe is sufficiently potent to allow the emergence of consciousness.

Supporting information

This material is available from the Supplementary data section and can be downloaded here.

Statements and Declarations

Data Availability

This study presents a theoretical framework and does not report new empirical data. Details regarding computational simulations based on the presented formalism, where applicable, may be found in cited references or can be requested from the corresponding author.

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