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Quantum process semantics

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Abstract

The paper describes a model of subjective goal-oriented semantics extending standard «view-from-nowhere» approach. Generalization is achieved by using a spherical vector structure essentially supplementing the classical bit with circular dimension, organizing contexts according to their subjective causal ordering. This structure, known in quantum theory as qubit, is shown to be universal representation of contextual-situated meaning at the core of human cognition. Subjective semantic dimension, inferred from fundamental oscillation dynamics, is discretized to six process-stage prototypes expressed in common language. Predicted process-semantic map of natural language terms is confirmed by the open-source word2vec data.

1 Introduction

Problem While effective in many recognition, classification, and combinatorial-type tasks, modern artificial intelligence does not approach human-level performance in several vital areas. Making decisions in novel situations, solving ill-defined problems, extracting knowledge from data, understanding of natural language, and other cognitive routines of humans are very difficult to algoritmize Brachman (2002); Sheth et al. (2019); Sowa (2015). Taking into consideration computational powers thrown at these tasks, incomparable to 10-20 watts of average human brain, this indicates that the encountered obstacle is of deep conceptual nature.

Root of the issue is identified by noting that the mainstream approaches simulate meaning of visual, textual, and other information types as their objective quality - a «content». Classical and contemporary studies, in contrast, indicate that semantics of a sign is not a property that can be discovered by a measurement algorithm; instead, it is constructed by a subject from the context perceived through stereotypes of his own mind Bruner (1990); Cornejo (2004); De Saussure (1959); DeGrandpre (2000); Firth (1935); von Glasersfeld (1995); Kintsch & Mangalath (2011); Langleben (1981); Ogden & Richards (1923); Stokhof (2002). Ignorance of this basic fact explains inefficiency of modern AI in cognitive tasks of inherently subjective nature.

Approach Fundamental problems need fundamental solutions. The approach developed below consists in finding a unit of information addressing subjectivity in explicit way and stimulating the algorithms to deal with this aspect of cognition. The candidate structure is already developed in physics to model atomic-scale phenomena nearly a century ago. It accounts for the novel type of information, carried by electrons, photons, and other well-isolated individual systems, that currently is the basis of quantum communication and computing Jaeger (2019); Nielsen & Chuang (2010).

Applicability of quantum information is not limited to elementary physical systems. With intuitive correspondence to psychological terms, quantum theory allows to describe irrational decision making, unexpected game equilibria, collective behavioral patterns, and understanding of natural language challenging classical modeling approaches Asano et al. (2015); Busemeyer & Bruza (2012); Khrennikov (2010, 2015); Khrennikov et al. (2019). Here, contextuality of quantum information allows to account for dependence of meaning on the context of an individual cognitive act Aerts et al. (2000); Basieva et al. (2018); Blacoe et al. (2013); Bruza (2008); Surov et al. (2019), thereby providing subjective ingredient missing in the classical approaches to semantic modeling.

Requested combination of objective and subjective aspects of information is achieved already in the simplest quantum-theoretic structure called qubit. In particular, qubit state allows to represent information contexts in spherical structure where polar coordinates stand for objective and subjective dimensions of cognition. This enables novel methods of analysis revealing regularities of semantics and decision making invisible from objectivist perspective Surov (2020). This work develops the qubit information structure supplementing it with a map of subjective dimension. The result is a scheme of semantic representation explicitly accounting for subjective contextuality of meaning.

Plan of the paper Section 2 introduces essential background, including quantum representation of contexts and the qubit semantic space following

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Surov (2020). Section 3 describes the main innovation of this paper, namely a scheme of subjective semantic dimension based on a circular process structure. Section 4 reports experimental testing of the model. The predicted process-semantic structure is found in 300-dimensional word2vec data by original analysis method. The result is compared with the existing semantic maps.

Section 5 shows how quantum semantics integrates aspects of human cognition discovered by diverse schools of research. In particular, process-causal and pragmatic-relativity views of semantics find expression in the quantum approach. Further, qubit semantic structure is shown to have qualities of dynamic archetype ubiquitously manifested in culture and science. Outlook section 6 indicates several implications of the result in philosophical and practical perspectives.

2 The Qubit

The announced unit of information accounts for the simplest behavioral situation – a choice between two mutually exclusive alternatives, imposed on a subject as external constraint. Simplification of this setup leads to single-option dynamics typical for inert deterministic systems; prolonged behavioral processes including multiple-option decisions, on the other hand, are expressible through sequences or trees of binary choices. The considered setup therefore constitutes an elementary behavioral prototype, absent in classical behaviorist approach Watson (1913).

This section describes mathematics and geometry of the considered information unit, known in quantum theory as qubit Jaeger (2007); Nielsen & Chuang (2010), following methodology of its application to behavioral modeling as described in Surov (2020). Sections 2.1 and 2.3 introduce relevant aspects of the model, with necessary generalization developed in Section 2.2.

2.1 Pure context representation space

The considered behavioral situation is formalized as a choice between two options labeled as “1” and “0”. Making of this decision requires estimation of the corresponding probabilities $p(1)$ and $p(0)$ that sum to 1 since the outcomes are mutually exclusive. The required computation is based on the information received by the considered subject (behavioral system) from its environment. All this information called *context* is subjectively mapped to a point on a three-dimensional unit-radius sphere built on the poles representing outcomes 1 and 0 as shown in Figure 1. In the following, this sphere developed in physics by A. Poincaré and F. Bloch is referred to as Bloch sphere.

2.1.1 Basic math

Any point on the Bloch sphere corresponds to a vector $|\psi\rangle$ superposing the basis vectors $|0\rangle$ and $|1\rangle$ representing the decision alternatives:

$$\begin{aligned} |\psi\rangle &= \cos\frac{\theta}{2}\,|0\rangle + e^{i\phi}\sin\frac{\theta}{2}\,|1\rangle\,, \\ |\psi\rangle &= \begin{bmatrix}\cos\theta/2\\ e^{i\phi}\sin\theta/2\end{bmatrix}, \quad |0\rangle = \begin{bmatrix}1\\0\end{bmatrix}, \quad |1\rangle = \begin{bmatrix}0\\1\end{bmatrix}, \end{aligned} \tag{1}$$

where θ and ϕ are polar and azimuthal angles defining position of the point. Vector $|\psi\rangle$ thus represents context within which choice between basis alternatives $|0\rangle$ and $|1\rangle$ is being made. The space containing context representation vectors (1) then functions as task-specific cognitive space of the subject.

Contrary to the standard Euclidean geometry where orthogonality of vectors is visualized by right angle between them, in the Bloch sphere basis vectors $|0\rangle$ and $|1\rangle$ are opposite to each other. The difference arises due to complexity of coefficients exemplified in (1) by complex exponent $e^{i\phi} = \cos\phi + i\sin\phi$. Sphere in real three-dimensional space is thereby equivalent to the two-dimensional complex (Hilbert) space of vectors $|\psi\rangle$.

In the context $|\psi\rangle$, probabilities of alternative decisions are computed as

$$\begin{aligned} p(0) &= |\langle 0|\psi\rangle|^2 = (\cos\theta/2)^2, \\ p(1) &= |\langle 1|\psi\rangle|^2 = (\sin\theta/2)^2, \quad p(0)+p(1) = 1, \end{aligned} \tag{2}$$

where $\langle\cdot|\cdot\rangle$ denotes overlap (scalar product) of the two vectors, so that e.g. $\langle 0|1\rangle = 0$, $\langle 0|0\rangle = \langle 1|1\rangle = \langle\psi|\psi\rangle = 1$. Probabilities (2) are proportional to the lengths of segments to which projection of $|\psi\rangle$ divides the diameter 1-0. That is, the closer context representation $|\psi\rangle$ is to the north pole of a sphere, the higher is probability $p(1)$, and the lower is probability $p(0)$. In representation (1), polar angle θ thus quantifies subjective conduciveness of contexts for choosing the alternative behavioral options, measurable through decision probabilities (2).

2.1.2 Decision and collapse of representation space

According to the model just described, a particular potential decision $0/1$ generates the task-specific Hilbert space where any context is subjectively represented by some qubit state (1). Equivalently, the latter represent different points of view, from which behavioral alternative $0/1$ can be considered.

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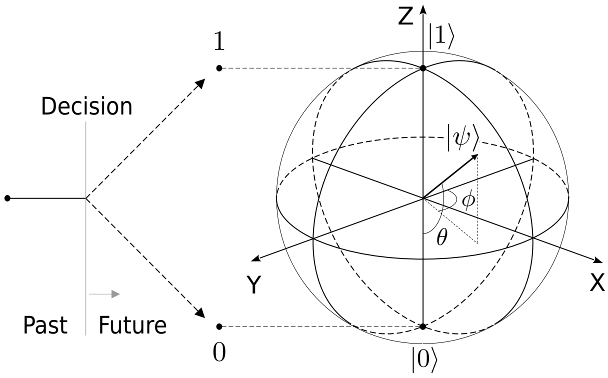

Figure 1: The unit-radius Poincaré-Bloch sphere visualizing quantum model of a binary choice. Pure qubit vector state (1) pointing to the surface of the sphere represents the context of decision relative to behavioral alternatives 1 and 0 defining poles of the sphere. θ and ϕ are polar and azimuthal spherical coordinates.

At the moment of actual decision, however, one of the potential alternatives 0/1 actualizes while the other is irreversibly discarded. The basis alternative disappears and representation space collapses, so that different contexts and points of view cease to make their task-specific sense.

The collapsing process can be visualized as projection of the initial vector (1) from the surface to the diameter of the Bloch sphere. For observers aware of the decision made, the final point is either the north or the south pole representing the actualized option. Otherwise, the point lies somewhere on the diameter of the Bloch sphere dividing it according to subjective judgment of probabilities. In the case of no bias, this position is given by probabilities (2) defined by orthogonal projection of vector $|\psi\rangle$ to the diameter.

2.2 Partially-coherent context representation

The above model of pure, i.e. maximally coherent context representation is developed for an ideal behavioral case, exemplified e.g. by choice where to turn on a T-shaped crossroad made by a subject right on the spot. To account for realistic situations, this extreme is generalized at least in the following aspects.

2.2.1 Causes of decoherence

1. Degree of subjective control
   A subject's control over his behavior is not necessarily full. For exam-

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ple, upon approaching the crossroad a traveler may follow a navigator selecting either of the two options according to its program. In this case, the true subject is author of the navigation algorithm, while a person on the ground merely executes his decision. Resolution of such behavioral uncertainty is (partially) predetermined in advance and therefore is not (fully) affected by contextual information perceived by the traveler.

2. Cognitive fragmentation
A subject may be unable to fit all the perceived contextual information to a single cognitive representation (1). In the above example, the right track may have poor surface, while the left one may pass over a broken bridge. If these factors are not accommodated in a single mind-picture (also known as psychological gestalt Köhler (1992)), then the corresponding fragments i of a unitary context are mapped to separate cognitive representations $|\psi_i\rangle$.

3. Under-defined basis
The target behavioral alternative generating context representation space itself can be ambiguous. For example, rainy weather favors going for mushrooms but is bad to mow hay, so that corresponding representations $|\psi_i\rangle$ of this context differ for different basis alternatives. Accordingly, when the behavioral basis is underdefined, the effective representation of contexts has to be averaged over multiple pure states analogous to the previous case.

In all of these cases, representation of the behavioral context does not lie on the surface of the Bloch sphere as shown in Figure 1. The first case is analogous to the already-made, but subjectively unknown decision considered in Sect. 2.1.2, so that corresponding context representation has to be located closer to the diameter of the Bloch sphere. Second and third cases require averaging over several context representations, leading to the similar effect called decoherence Zurek (1991). Corresponding representation of contexts requires extension of the pure case considered in Section 2.1 to the mixed-state formalism developed below.

2.2.2 Matrix formalism for incoherent representations

According to the above, the required generalization is expected to allow context representations to populate not only the surface of the Bloch sphere, but also its interior. This is achieved by extending pure state (1) to matrix

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form via the outer product of vector $|\psi\rangle$ with itself

$$\hat{\rho}_{\text{pure}}(\theta,\phi) = |\psi\rangle\langle\psi| = \begin{bmatrix} \cos^2\dfrac{\theta}{2} & e^{-i\phi}\dfrac{\sin\theta}{2} \\ e^{i\phi}\dfrac{\sin\theta}{2} & \sin^2\dfrac{\theta}{2} \end{bmatrix}, \tag{3}$$

where $\langle\psi| = |\psi\rangle^\dagger$ is complex-conjugate (Hermitian) transpose of $|\psi\rangle$. Diagonal elements of pure-state matrix (3) are decision probabilities (2), while its off-diagonal elements are cross-products of vector components.

Going beyond the pure state limit is achieved by considering mixtures of several pure matrices (3). For example,

$$\frac{\hat{\rho}_{\text{pure}}(\theta,\phi) + \hat{\rho}_{\text{pure}}(\theta,\phi+\pi)}{2} = \begin{bmatrix} \cos^2\dfrac{\theta}{2} & 0 \\ 0 & \sin^2\dfrac{\theta}{2} \end{bmatrix} \tag{4}$$

describes projection of pure state (3) shown in Figure 1 to the diameter of the Bloch sphere. In general, any trace-one mixture of several pure representations (1)

$$\hat{\rho} = \sum_i w_i\, |\psi_i\rangle\langle\psi_i|\,, \quad \sum_i w_i = 1, \tag{5}$$

is valid context representation. Compared to fully decoherent (4) and pure state (3), (density) matrix calculus allows to account for partially incoherent representations motivated in Sect. 2.2.1, as well as the result of the quantum state collapse discussed in Sect. 2.1.2.

2.2.3 Incoherent representations in the Bloch ball

Incoherent representation of contexts is visualized by decomposing matrix (5) as

$$\hat{\rho} = \begin{bmatrix} \rho_{00} & \rho_{01} \\ \rho_{10} & \rho_{11} \end{bmatrix} = \frac{1}{2}\begin{bmatrix} 1-s_z & s_x - is_y \\ s_x + is_y & 1+s_z \end{bmatrix} \tag{6}$$

where $-1 \le s_\mu \le 1$ are components of three-dimensional Stokes vector[1].

$$\vec{S} = \begin{bmatrix} s_x \\ s_y \\ s_z \end{bmatrix}, \qquad \begin{aligned} s_x &= R\sin\theta\cos\phi, \\ s_y &= R\sin\theta\sin\phi, \\ s_z &= -R\cos\theta. \end{aligned} \tag{7}$$

[1] In optics, these values called Stokes parameters are used to quantify polarization states of light Mandel & Wolf (1995).

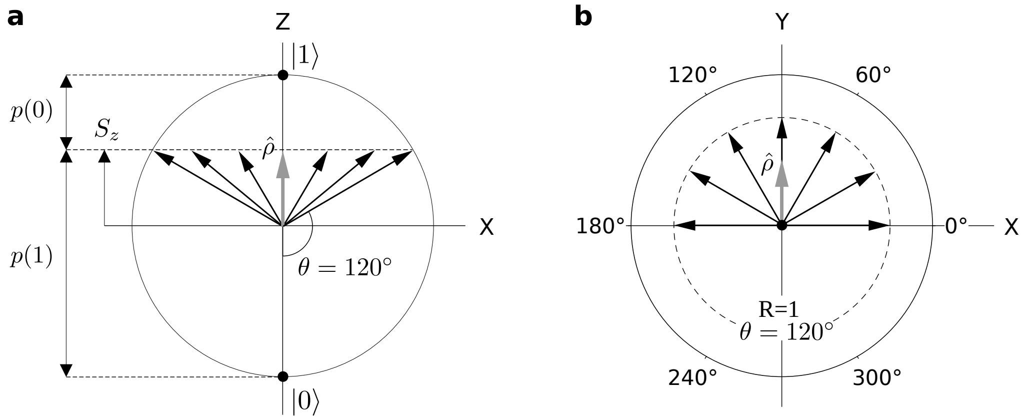

Figure 2: Example of incoherent context representation $\hat{\rho}$ (gray) formed by mixing of several pure representations $|\psi_i\rangle$ (black) (5) as required to model various sources of cognitive decoherence described in Section 2.2.1. Both pure and mixed representations are shown by Stokes vector $\vec{S}$ (7) pointing to the surface and to the interior of the Bloch ball respectively. Panels (a) and (b) show projections to XZ and XY planes.

For the pure state (3), these coefficients with $R = 1$ are Cartesian coordinates of the unit-length vector shown in Figure 1.

For $0 < R < 1$, point with coordinates (7) is located below the Bloch sphere's surface, while $R = 0$ corresponds to the center of the sphere and maximally incoherent state (4) with $\theta = \pi/2$. Parameter R defining length of vector $\vec{S}$ thus quantifies coherence of the context representation (6). This is a third dimension introduced by matrix formalism in addition to spherical angles θ and ϕ defining pure state (1), (3).

Geometry of Stokes vectors allows to visualize mixing of several pure representations producing incoherent mixture described in Section 2.2.1. This is exemplified in Figure 2, where seven vectors $|\psi_i\rangle$ shown by black arrows uniformly occupy an arc on the Bloch sphere defined by azimuthal range $0° \leq \phi \leq \phi_{\max} = 180°$ and constant polar angle $\theta = 120°$. With identical weights w_i, the resulting mixed state $\hat{\rho}$ (5) is shown by Stokes vector (7) depicted as gray arrow. Its Z component $s_z = -\cos 120° = 0.5$ is the same as for all $|\psi_i\rangle$, $s_y \approx 0.46$, and $s_x = 0$ due to symmetry.

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2.2.4 Similarity, purity and distance measures

Similarity between the two arbitrary matrix representations (6) can measured by quantity

$$\begin{aligned} &\mathrm{Tr}\left(\hat{\rho} * \hat{\sigma}\right) = \rho_{00}\sigma_{00} + \rho_{11}\sigma_{11} + 2\mathrm{Re}\left(\rho_{01}\sigma_{10}\right), \\ &0 \leq \mathrm{Tr}\left(\hat{\rho} * \hat{\sigma}\right) \leq 1, \end{aligned} \tag{8}$$

where $*$ denotes matrix multiplication and $\mathrm{Tr}(\cdot)$ returns sum of the diagonal elements of the argument matrix. In terms of the corresponding Stokes vectors (7), similarity (8) is expressed as

$$\mathrm{Tr}\left(\hat{\rho} * \hat{\sigma}\right) = \frac{1 + \vec{S}_\rho \cdot \vec{S}_\sigma}{2}, \tag{9}$$

where $\cdot$ denotes Euclidean scalar product.

Expression (8) produces decision probabilities (2)

$$p(i) = \mathrm{Tr}\left(\hat{\rho} * \hat{\sigma}\right) = \langle i|\, \hat{\rho}\, |i\rangle = \rho_{ii}, \tag{10}$$

with pure representation (3) and $\hat{\sigma} = |i\rangle\langle i|$ being matrix projecting any pure state to the measurement outcome $i \in \{0, 1\}$. Decision probabilities thus essentially are similarities between the context representation $\hat{\rho}$ and a particular outcome represented by $\hat{\sigma}$.

With $\hat{\sigma} = \hat{\rho}$, expression (9) defines *purity* of density matrix $\hat{\rho}$

$$\begin{aligned} &P \equiv \mathrm{Tr}\left(\hat{\rho}^2\right) = \frac{1 + |\vec{S}|^2}{2} = \frac{1 + R^2}{2}, \\ &0.5 \leq P \leq 1, \end{aligned} \tag{11}$$

that is similarity of the density matrix $\hat{\rho}$ to itself. For the example mixed representation shown in Figure 2 with $|\vec{S}| = R \approx 0.68$, the corresponding purity is $P \approx 0.73$.

Euclidean difference between Stokes vectors is also metric in space of density matrices, called trace distance Nielsen & Chuang (2010) and defined as

$$\begin{aligned} &\mathcal{D}(\hat{\rho}, \hat{\sigma}) = \frac{\mathrm{Tr}\,|\hat{\rho} - \hat{\sigma}|}{2} = \frac{|\vec{S}_\rho - \vec{S}_\sigma|}{2}, \\ &|\hat{\rho}| = \sqrt{\hat{\rho}^\dagger \hat{\rho}}, \quad 0 \leq \mathcal{D} \leq 1. \end{aligned} \tag{12}$$

This metric quantifies distance between any two context representations (6).

2.3 Qubit semantic space

In the model developed above, the Bloch ball functions as a subjective context representation space generated by a particular behavioral alternative with outcomes 1 and 0 defining the two poles. In this cognitive space, the contexts are represented by variables $0 \leq \theta \leq \pi$, $0 \leq \phi \leq 2\pi$, and $0 \leq R \leq 1$ according to their subjective relation to the considered behavioral choice. In particular, polar angle θ quantifies subjective favorability of contexts for the potential decisions via probability relations (2), while radial dimension R accounts for mixing of several representations due to factors discussed in Section 2.2.1. This value-based representation qualifies the Bloch ball as a particular type of semantic space De Jesus (2018); Gärdenfors (2014); Kharkevich (1960); Kolchinsky & Wolpert (2018).

Taken alone, polar and radial dimensions θ, R function within the classical-probabilistic modeling paradigm, limitations of which are noted in the Introduction. However, quantum-theoretic structure of the qubit state space includes this pair only as a part of a broader spherical geometry where an additional, azimuthal dimension ϕ is indispensable. This results in unique features of quantum semantic model reported in this paper. Without loss of generality, these properties are described in the rest of this section for the case of maximal coherence with $|\vec{S}| = R = P = 1$ (11).

2.3.1 Objective and subjective dimensions of the qubit semantic space

Qubit representational space is subjective by definition; in this space, both polar and azimuthal dimensions are not objective features of the contexts per se, but defined relative to the basis behavioral uncertainty within individual cognition of the considered subject. Still, in certain sense polar dimension can be called objective and azimuthal one can be called subjective. This difference in "second-order" subjectivity, fundamental for function of the qubit semantic space, is explained in this subsection.

As expressed by relations (2), polar angle θ is one-to-one mapped to measurable decision probabilities $p(i)$. Once the latter are known, θ is uniquely defined as $2\arccos\sqrt{p(0)} = 2\arcsin\sqrt{p(1)}$ with no interpretational freedom. In this sense, polar dimension of qubit space (1) is *objective* in nature. The same absence of interpretational freedom is fundamental feature of classical (Kolmogorovian) probability spaces, unambiguously defined by observable data. In fact, polar angle range $0 \leq \theta \leq \pi$ is isomorphic to the diameter 0-1 of the Bloch sphere as shown in Figure 2(a) visualizing classical probability space of binary random variable 0-1.

Azimuthal dimension of the qubit semantic space is of different quality. As evident from Figure 1, azimuthal dimension ϕ of the qubit state (1) is orthogonal to Z axis and therefore does not enter decision probabilities (2) directly; for any θ (except degenerate cases $\theta = 0, \pi$ and $R = 0$) there is continuous range of possible representations with $0 \leq \phi \leq 2\pi$ corresponding to the same decision probabilities $p(i)$. In other words, azimuthal location of the context is not uniquely defined by observable behavior. Azimuthal phase ϕ thus functions as internal degree of freedom affecting the outside only indirectly through composition relations between different contexts illustrated below. This dimension of the qubit state space thus represents *subjective* aspect of semantics uniquely accounted by quantum approach.

2.3.2 Semantic triad

As noted above, "double-subjective" azimuthal dimension of the qubit semantic space does not affect observable decision probabilities as far as a single context is considered by any subject. It comes into play when several contexts have to be organized jointly in relation to the same decision alternative.

The minimal example is composition of three representations, enacted e.g. in perception of, and decision making in a novel context c based on known contexts a and b Surov (2020). This is realized via linear combinations of type

$$\begin{gathered}|\psi_c\rangle = x_a |\psi_a\rangle + x_b |\psi_b\rangle = \\ e^{i\Phi_c}\begin{bmatrix}\cos\frac{\theta_c}{2} \\ e^{i\phi_c}\sin\frac{\theta_c}{2}\end{bmatrix} = \begin{bmatrix} x_a\cos\frac{\theta_a}{2} + x_b\cos\frac{\theta_b}{2} \\ x_a e^{i\phi_a}\sin\frac{\theta_a}{2} + x_b e^{i\phi_b}\sin\frac{\theta_b}{2}, \end{bmatrix}\end{gathered} \tag{13}$$

called superpositions, where $|\psi_i\rangle$ are pure qubit states (1) and $x_{a,b}$ are complex-valued coefficients. In the composed context c, decision probabilities (2) given by polar angle θ_c depend on azimuthal phases of vectors $|\psi_a\rangle$ and $|\psi_b\rangle$, as well as on parameters $x_{a,b}$. Simplest example of composition (13) is

$$\begin{aligned}|\psi_a\rangle =& \frac{|0\rangle + |1\rangle}{\sqrt{2}}, \\ |\psi_b\rangle =& \frac{|0\rangle + e^{2i\pi/3}|1\rangle}{\sqrt{2}}, \\ |\psi_c\rangle =& e^{-i\pi/3}|\psi_1\rangle + e^{i\pi/3}|\psi_2\rangle = \frac{|0\rangle + e^{-2i\pi/3}|1\rangle}{\sqrt{2}},\end{aligned} \tag{14}$$

where zero azimuth $\phi = 0$ is identified with representation $|\psi_a\rangle$ of context a, while $\phi = \pm 2\pi/3$ correspond to contexts b and c. Vectors (14) form an equilateral triangle in the equatorial plane of the Bloch sphere.

Superposition of type (13) relate any three non-degenerate representations; this linear-algebraic feature of quantum states allows a subject to accommodate any number of contexts in a single qubit space, establishing subjective relations between them as explained in Section 3. Triple of representations (13),(14) thus functions as a minimal carrier of meaning, called semantic triad Surov (2020). Triadic nature of semantics and natural cognition in general (Sowa, 2000, ch.2) is the basis for the quantum process structure described in the following.

3 Process-based map of the qubit semantic space

This section specifies type of subjective relations between context representations accounted by azimuthal dimension mentioned in Section 2.3. The result is fully interpretable structure of the qubit semantic space.

3.1 Main principle

From the times immemorial, activity of humans was structured by cycles of nature. Hunting-gathering, agriculture, building, and other practices gave result only when performed in particular order synchronized with the year and day-night cycles. For every climate-geographical zone, this produced natural order of events violation of which threatened survival of individuals and species. Proper distribution of activities and resources over environmental cycles was therefore of vital importance. Process-based cognition of humans and other species developed to address this task by prognostic and planning activities Bubic et al. (2010).

Technology largely relieved us from environmental press, but not from the need for prognostic and planning activity; rather, in modern technogenic environment these tasks became even more critical and complex. On evolutionary scale, however, these changes happened nearly instantly. Modern human mind runs on the same neuronal hardware and uses the same cognitive heuristics as millennia ago Harari (2014).

Process cycle in azimuthal dimension Central idea of this paper is that cyclical processes of nature mentioned above are ingrained in human cognition to boost its prognostic capabilities. Common circular topology of these processes condenses to a universal process-based template shown in Figure 3(a), unconsciously shaping cognition and behavior of living organisms.

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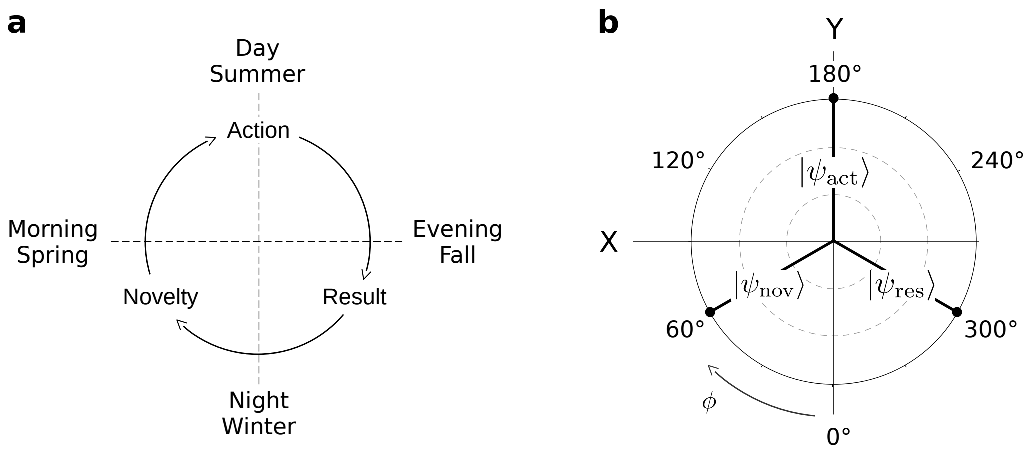

Figure 3: a: Basic triad of *Novelty*, *Action*, and *Result* process stages roughly mapped to the archetypal day-night and year cycles. b: The same stages represented by symmetric triad of pure qubit states of type (14) in the equatorial plane of the Bloch sphere.

This principle is readily incorporated in the quantum model of context representation developed in Section 2. In particular, cyclical process template is mapped to the azimuthal coordinate ϕ of the qubit semantic space as shown in Figure 3. The contexts are mapped to distinct ranges of ϕ according to their process-based functional relation to the basis behavioral alternative generating the qubit representation space. Logic of this mapping is explained in Section 3.2.

Discretization, process stages, and context classes Akin to other cognitive domains, continuous process dimension of the qubit semantic space is discretized to a limited number of (more or less) natural categories Rosch (1975)[2]. Accordingly, the contexts are sorted to the same number of process-semantic classes as in standard categorization tasks Rehder (2010); Vergne & Wry (2014), with central prototypes of the categories represented by vectors $|\psi_i\rangle$ as exemplified in Figure 3(b).

In choice of the process categories, the simplest approach would be to divide the azimuthal dimension in the base of two, generating 2,4,8...-item taxonomies depending on the required detalization. Binary oppositions, however, do not align with triadic nature of subjective semantics; closed and stable semantic structures are formed not by pairs, but by triples of cognitive

[2]Basically, discreteness is cognitive solution for robust and efficient sensing, processing, storage, and transmission of information Tee & Taylor (2020).

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states represented by semantic triads of type (13) Surov (2020). In this work, azimuthal process dimension is discretized to six stages generating the same number of the process-semantic context classes. This number, located at the safe side of attention capacity for 7 ± 2 objects at once Miller (1956); Saaty & Ozdemir (2003), is chosen as balance between resolution and simplicity[3].

3.2 Semantic hexagon of process stages

3.2.1 Three primary stages

The basic day-night cycle structuring human activity (Section 3.1) has the following distinct stages:

1. The cycle begins in the morning that is a time to face novelty. Newly setting daylight facilitates assessment of the situation, recognition on problems and tasks to be addressed throughout the day.

2. A midday is a period of maximum activity. In the pre-industrial age, daylight hours were the most conducive period for hunting, gathering, building, agriculture, and other vital activities.

3. The cycle is finished in the evening. Diminished working energy and lighting are appropriate for soft indoor activities like estimation of the results and preparation for the next cycle.

The year cycle is structured analogously with spring, summer and fall roughly corresponding to the above stages of the day. Winter (in the northern hemisphere) corresponds to night when cognition is shut down and activity is at minimum; this recovery period goes mainly in an automated mode with minimal behavioral optionality and decision making.

Each of three cycle stages defines a specific class of contexts describing stage-specific activities. Accordingly to the description above, these classes are called *Novelty*, *Action*, and *Result* as shown in Figure 3(a) and have the following functions:

1. Novelty
   Contexts describing new factors motivating the behavioral uncertainty resolved by a subject.

[3]Refined structures like a clock with 12-mark dial might be useful for technically-assisted cognitive applications akin to signal processing technologies Goodman & Silvestri (1970); Horner & Leger (1985); Kakande et al. (2011); Pavelyeva (2018); Ten Oever et al. (2020).

2. Action
   Contexts describing activities realizing the considered decision.

3. Result
   Contexts describing the outcomes, implications, and consequences of the considered decision.

According to Section 3.1, contexts allocated to either of these classes map to specific ranges in the azimuthal dimension of the qubit semantic space.

Semantic triad of main process stages In the simplest case, central prototypes of *Novelty*, *Action*, and *Result* context classes are represented by vectors $|\psi_{\mathrm{nov}}\rangle$, $|\psi_{\mathrm{act}}\rangle$, and $|\psi_{\mathrm{res}}\rangle$ forming symmetric configuration shown in Figure 3(b). Choice of zero azimuth is a matter of convenience. This paper follows setting $\phi(Novelty) = 60°$ so that $\phi(Action) = 180°$ and $\phi(Result) = 300°$.

Triple of vectors $|\psi_{\mathrm{nov}}\rangle$, $|\psi_{\mathrm{act}}\rangle$, $|\psi_{\mathrm{res}}\rangle$ forms semantic triad described in Section 2.3.2, with composition rules (13),(14) reflecting relations between the process-semantic prototypes. In natural language, these relations are expressed by circular definitions of the basis context classes:

1. *Novelty* is a *Result* of previous *Action*;

2. *Action* is a move from *Novelty* to *Result*;

3. *Result* of *Action* leads to a potential *Novelty*.

Process-based classes *Novelty*, *Action*, and *Result* thereby form a minimal process-semantic taxonomy where each element is necessary to define the other two.

3.2.2 Three intermediate stages

In practice, *Novelty* is often not obvious; it results from diagnostics and/or analysis of the current state of affairs that is an elaborate process by itself Rasiel & Friga (2002). Similarly, *Action* does not follow the *Novelty* immediately, but requires setting goals regarding the newly identified factor and developing a plan for their achievement. The *Result* also does not follow *Action* at once. Usually, the first and major part of effort goes without any considerable outcome; when it arrives, the action moves to a distinct stage responding to the received feedback.

These three additional stages, further referred to as *Sensing*, *Goal-Plan*, and *Progress*, supplement the basic process structure shown in Figure 3 generating three new classes of contexts. This refinement of the process taxonomy

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is validated by distinctive difference of the new stages from three primary ones.

Relation to the primary stages Continuing the symmetric configuration shown in Figure 3(b), central prototypes of three intermediate context classes $|\psi_{\text{sens}}\rangle$, $|\psi_{\text{gp}}\rangle$, $|\psi_{\text{prog}}\rangle$ are positioned halfway between the primary ones as shown in Figure 4. *Sensing* thus falls opposite to *Action*, *Goal-Plan* is opposite to *Result*, and *Progress* opposes *Problem*, so that

$$\begin{aligned} \hat{U}\,|\psi_{\text{act}}\rangle &= |\psi_{\text{sens}}\rangle\,, \\ \hat{U}\,|\psi_{\text{nov}}\rangle &= |\psi_{\text{prog}}\rangle\,, \\ \hat{U}\,|\psi_{\text{res}}\rangle &= |\psi_{\text{gp}}\rangle\,, \\ \hat{U} &= |0\rangle\langle 0| - |1\rangle\langle 1| = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}, \end{aligned} \tag{15}$$

where $\hat{U}$ is phase flip operator rotating the process stage by 180° in the azimuthal dimension, realizing a particular kind of process-semantic negation.

In sum, azimuthal dimension of the Bloch sphere is now discretized to six process-semantic bands

Sensing - *Novelty* - *Goal-Plan* - *Action* - *Progress* - *Result*

covering azimuthal sectors of 60° each. The same structure holds for incoherent context representations as described in Section 2.2.3. Stokes vectors $\vec{S}$ corresponding to each context class then occupy sector areas defined by the same range of the ϕ as for pure states, including interior of the circle shown in Figure 4.

3.2.3 Example

Organization of contexts based on this process structure is illustrated by the following example.

Consider a subject choosing whether to go for a PhD (1) or not (0). This binary alternative defines a Hilbert space for context representation described in Section 2. The following list exemplifies how the contexts are mapped to the azimuthal dimension ϕ of this space according to the scheme shown in Figure 4.

1. *Sensing*, $330° < \phi < 30°$
   This range accommodates contexts pointing to the novelty that is addressed by the considered behavioral alternative. Inefficient behavior, wrong decisions, failures and defeats (likely resulting from previous actions) are placed here.

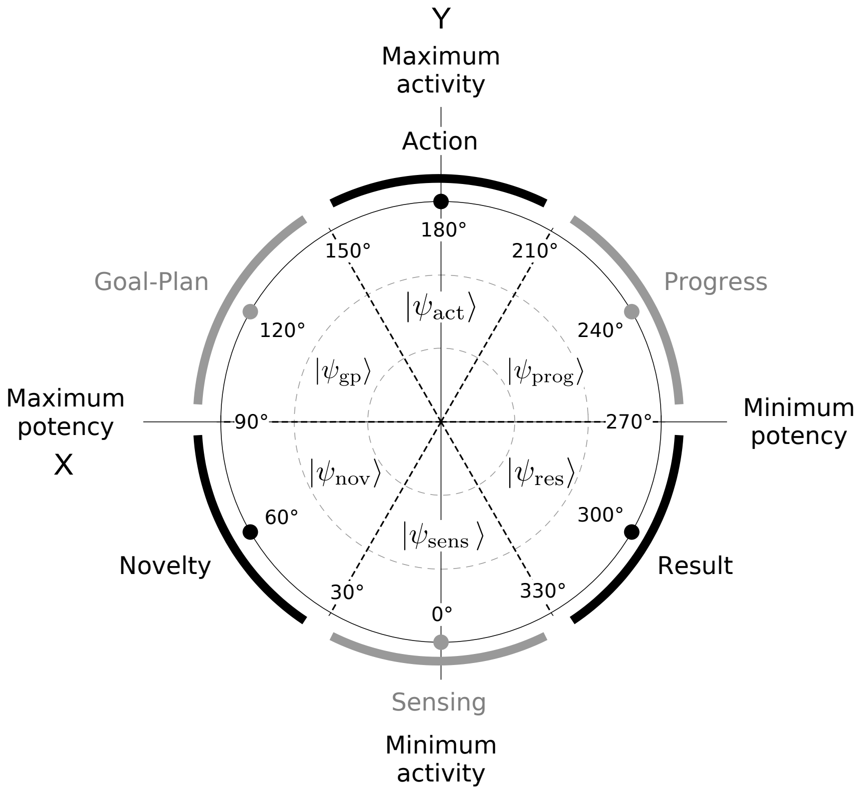

Figure 4: Process structure of azimuthal dimension in the qubit semantic space refining three-stage scheme shown in Figure 3. The process starts with *Sensing* contexts of minimum activity and proceeds in the clockwise direction to the *Novelty*, *Goal-Plan*, *Action*, *Progress*, and *Result*. Black and gray dots and bands indicate central prototypes and azimuthal ranges of the main and intermediate context classes.

2. *Novelty*, $30° < \phi < 90°$
   This range contains contexts describing the newly revealed factor, e.g. low level of skills and knowledge insufficient for the activity of a subject.

3. *Goal-Plan*, $90° < \phi < 150°$
   This range is for contexts setting objectives regarding the identified novelty and describing strategy for achieving them. If the goal is to get educated with a PhD degree, then the plan by all likelihood would include choosing the university, collecting necessary resources, passing entrance examinations, going through studies, making a research, etc.

4. *Action*, $150° < \phi < 210°$
   Here are the contexts describing particular activities, efforts and diffi-

culties involved in realization of the plan. Studying practice, research activity, images of the initial-stage hard work belong to here.

5. *Progress*, $210° < \phi < 270°$
   This sector is populated with contexts describing intermediate results and feedback-related work. Established cooperation with the colleagues, passing examinations, approbation of the research results, defense of the degree are described here.

6. *Result*, $270° < \phi < 330°$
   This azimuthal range accounts for the result of the considered decision. Contexts describing new level of competence and skills, the desired profession, novel social status, other outcomes and consequences of the action are accommodated here.

3.3 Cartesian axes of semantic space

Although qubit semantic space is more naturally introduced in spherical coordinates as it is done above, Bloch-sphere picture also allows to interpret is in terms of three Cartesian dimensions X, Y, Z indicated in Figure 1. Semantic function of these axes is outlined below.

3.3.1 Z axis: Evaluation

The contexts of each process stage are subjectively evaluated by personal measure of appropriateness (conduciveness, favorability) in relation to the considered decision. In the PhD example described above, entertainment can be considered as bad motivation for studying, in contrast e.g. to the need for skills and expertise. This subjective goal-directed estimation is quantified by probability of the positive decision $p(1)$, computed from the polar coordinate θ according (2); both are lower in the first case and higher in the second.

Both for coherent and incoherent context representations, the corresponding measure is Z component of Stokes vector $-1 \leq s_z \leq 1$ defining decision probabilities as visualized in Figure 2(a). This identifies Z axis of the Bloch sphere as **evaluative** dimension in the qubit context representation.

By themselves, six process stages introduced above are neither positive nor negative. The corresponding representations $|\psi_{\text{sens}}\rangle$, $|\psi_{\text{nov}}\rangle$, $|\psi_{\text{gp}}\rangle$, $|\psi_{\text{act}}\rangle$, $|\psi_{\text{prog}}\rangle$, $|\psi_{\text{res}}\rangle$ thus have s_z close to zero, so that the process circle shown in Figure 4 lies near to equatorial XY plane of the Bloch sphere.

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3.3.2 Y axis: Activity

Meaning of Y axis is obvious from definitions of the six stages and their mapping to the azimuthal XY plane shown in Figure 4. In accord with archetypal day-night and year cycles shown in Figure 3, maximally active *Action* context class opposes minimally active *Sensing* class. Y axis thus discriminates contexts according to the amount of associated (external) **activity**. Both in pure and mixed representations activity is measured by Y component of the Stokes vector $-1 \leq s_y \leq 1$, so that horizon $s_y = 0$ divides three active context classes *Goal-Plan*, *Action*, *Progress* from three passive classes *Result*, *Sensing*, and *Novelty*.

3.3.3 X axis: Potency

Horizontal axis in Figure 4 quantifies ability of the corresponding contexts to influence the whole process, and also behavioral freedom of the subject in these contexts. In a single word, this is further referred to as **potency**. Potency is at maximum between *Novelty* and *Goal-Plan* stages, where formulation of goals affects subsequent stages in the most profound way; at this point, a subject has maximal freedom to set direction of the process in deliberately chosen way. In contrast, after the *Progress* has been made, subsequent *Result* contexts unfold in largely predetermined manner, leaving to the subject a minimal freedom to change the course of events.

Both in pure and mixed representations, potency of a context is measured by X component of Stokes vector $-1 \leq s_x \leq 1$ that in Figures 3 and 4 is positive on the left and negative on the right. Vertical $s_x = 0$ divides positive-potency contexts where the activity is increasing and negative-potency contexts where the activity is decreasing. Accordingly, positive-activity contexts decrease potency, while negative-activity contexts increase potency. Fundamental role of this oscillation pattern in human cognition is further discussed in Section 5.

4 Experiment

The quantum process model of semantics described above is tested on natural language contexts pervading human cognition. The consideration is limited to single words being the most concise of linguistic contexts.

4.1 Process semantics of single words

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Context-dependent semantics As noted in Section2.3.1, meaning of no context is defined by itself; it always requires broader context, within which it is subjectively perceived and made sense of. This is also the case for single-word contexts considered in this section.

Consider, for example, the word `DOOR`. When accompanied by the word `broken`, it can entail an option to fix it (1) or not (0), to seek the intruder (1) or not (0), and countless other basis alternatives in relation to which the `DOOR` context would be ascribed to the *Problem*-class. Alternatively, `installation of the DOOR` can be a *Progress* for building a house. Just as easy, `opening` or `closing the door` may take part in the *Goal-Plan*, *Action*, *Result*, and *Reflection*-class contexts both in positive and negative value.

Taken alone, the context `DOOR` thus bears little process information. Averaging over different usage cases degrades coherence of its representation by "cognitive fragmentation" and "underdefined basis" mechanisms described in Section 2.2.1. The resulting representation of the single-word `DOOR` context therefore lies close to the origin of the Bloch ball, having $|\vec{S}| = R \ll 1$ and purity (11) close to the minimum.

Average-stable semantics However, not all words are as neutral. `Perception`, `Emergency`, `Idea`, `Strategy`, `Advantage`, `Outcome`, `Conclusion` clearly classify to definite context classes described in Section 3, thus carrying reliable process information largely irrespective of their linguistic environment. Corresponding quantum-state representations are therefore expected to have high process-semantic coherence even after averaging over multiple usage cases.

This observation allows to study process semantics on the existing lexical databases like WordNet Miller (1995) and Word2vec Mikolov et al. (2013) that summarize statistics of words' usage from large corpora of texts. Further discussion focuses on Word2vec data that align with the dimensional semantic structure considered in this paper more directly.

Source data: word2vec Word2vec data contain high-dimensional vector representations $\vec{w}_i$ of individual words and phrases w_i, obtained from a neural network trained to predict their neighbors throughout the corpus of natural language texts Mikolov et al. (2013). This implies averaging of all available usage cases, erasing context-sensitive semantics as described above. The remaining average-stable semantics still reflects useful relations between words, so that for example

$$\begin{aligned} \overrightarrow{king} - \overrightarrow{man} &\approx \overrightarrow{queen} - \overrightarrow{woman}, \\ \overrightarrow{Einstein} - \overrightarrow{scientist} &\approx \overrightarrow{Mozart} - \overrightarrow{painter}, \\ \overrightarrow{Windows} - \overrightarrow{Microsoft} &\approx \overrightarrow{Android} - \overrightarrow{Google}. \end{aligned} \tag{16}$$

This is the basis for expecting process semantics introduced in Section 3 to be found in the word2vec data. 300-dimensional vectors for 3 million of English words trained on the Google News corpus were taken from official source Google Code Archive (2013).

4.2 Building the qubit semantic space

Simplest way to observe process semantics in word2vec data would be to identify among 300 word2vec dimensions three corresponding to X, Y, and Z axes described in Section 3.3. However, this was not found possible; sorting 1000 most used English words by any of the first 10 word2vec dimension did not reveal any obvious regularity. Next, qubit semantic dimensions could be sought among the principal components of word2vec data. This also did not yield a result. Although the first several PCs do have interpretable meanings, the latter are not recognized as Evaluation, Activity, or Potency. In the 300 word2vec space, the process semantic axes are therefore not specific in their variance properties. They were identified with a different method based on the notion of semantic prototypes Lieto et al. (2017).

4.2.1 Z axis

Evaluation axis $\vec{Z}$ (Section 4.2.1) was found by requiring that average-stable positive and negative single-word contexts have positive and negative values of Z, respectively. Corresponding sets of four words for each evaluation extreme are listed in the first two lines of Table 1.

Analogous to semantic differences (16), the requested axis was set to

$$\vec{Z} = \vec{W}[1] - \vec{W}[0], \tag{17}$$

where $\vec{W}[i]$ are averages among four vectors within the positive and negative sets. For any word2vec word-vector $\vec{w}$, evaluation is now determined as

$$s_z = \vec{w} \cdot \vec{Z}, \tag{18}$$

where dot denotes scalar product in 300-dimensional word2vec space. This calculation was tested on 1000 of the most used English words. Sorting them on the value (18) returned top five words being flag, salute, capable, god, champ, while five words with lowest s_z are evil, dark, corrupt, rotten, greed.

Table 1: Words forming context-class prototypes corresponding to the poles of the Bloch sphere and six process stages shown in Figure 4.

Context class	Individual terms
1	good light well god
0	bad dark poor evil
Sensing	reflection deliberation expectation feeling perception intuition ponder observation rumination perspective attention insight prediction introspection
Novelty	factor issue shock surprise problem reason doubt query dilemma puzzle riddle mystery concern question
Goal-Plan	idea concept theory innovation strategy principle project design map plot motive intent purpose aim
Action	deal work compete cooperate engage solve maneuver implement execute fight manage strive construct develop explore
Progress	advance attain achieve gain regress accomplish fulfill produce increase earn yield recede output reach
Result	ending expiration completion harvest summation conclusion defeat victory score record final finish outcome aftermath

4.2.2 XY plane

The process semantic plane formed by X and Y axes was found as a single 300-dimensional complex-valued vector $\vec{\Omega}$ with real and imaginary components standing for Potency X and Activity Y dimensions of process semantics. Analogous to (18), any word2vec representation is mapped to this plane by taking scalar product of the corresponding vector $\vec{w}$ with $\vec{\Omega}$:

$$\vec{w} \cdot \vec{\Omega} = s_x + is_y, \tag{19}$$

where s_x and s_y are Activity and Potency components of Stokes vector (7) in the qubit semantic space representing a single-word context w in the quantum model described in Section 2. In particular, azimuthal phase ϕ computed as argument of complex-valued scalar product (19) determines position of the context in circular process dimension shown in Figure 4.

Vector $\vec{\Omega}$ was found by requiring that relation (19) works for six context classes described in Section 3 of the main text. To that end, *Sensing*, *Novelty*, *Plan*, *Action*, *Progress*, and *Result* classes were each populated by 15 class-specific terms listed in Table 1. Average of the corresponding mean-normalized word2vec vectors $\vec{w}$ in each class produced six 300-dimensional vectors

$$\vec{W}_k = \frac{1}{N}\sum_{i=1}^{N} \vec{w}_i^k, \qquad N = 15, \quad k = 1..6, \tag{20}$$

used as word2vec representations of six context classes. Due to decoherence mechanism described in Sections 4.1 and 2.2, this averaging decreases norms $|\vec{W}_k|$ relative to the mean-normalized individual terms with $\overline{|\vec{w}_i|} = 1$ to $|\vec{W}_k| = 0.53 \pm 0.02$.

For vectors (20), proper categorization to the process stages implies that

$$\vec{W}_k \cdot \vec{\Omega} = |\vec{S}_k|\, e^{i\Phi_k}, \qquad \Phi_k = 60°(k-1) \tag{21}$$

where expected azimuthal phases Φ_k of process-class prototypes are taken from Figure 4. To satisfy (21), $\vec{\Omega}$ was set to

$$\vec{\Omega} = \sum_{k=1}^{6} \vec{W}_k\, e^{i\Phi_k} = \vec{\mathrm{X}} + i\vec{\mathrm{Y}}, \tag{22}$$

which essentially is two-dimensional generalization of (17). Justification of this choice is given in Supplementary Material.

4.2.3 Process-semantic map

Relations (18) and (19) allow to map any word2vec representation $\vec{w}$ to the qubit space of averaged semantics (Section 4.1). By construction, the obtained vectors $\vec{s}$ are identified with Stokes vectors (7) visualizing qubit context representations of limited-coherence. This procedure was applied to six process-semantic prototypes (20) including total of 90 individual words listed in Table 1.

Z position of process-semantic prototypes Z positions of six prototypes $\vec{S}_k$ obtained from (20) and (18), -0.0075 ± 0.01, are practically equal to zero, as expected for evaluation-neutral process-semantic prototypes; the largest deviation of -0.04 is observed for the *Novelty* prototype populated with unbalanced negatively evaluated terms `doubt`, `shock`, `problem`, and `issue`. Smallness of Z positions allows reduces qubit semantic space to the process XY plane that is of primary interest. Corresponding positions of individual terms $\vec{s}$ and central-class prototypes $\vec{S}_k$ are calculated as described in Section 4.2.2. The resulting graphic is shown in Figure 5.

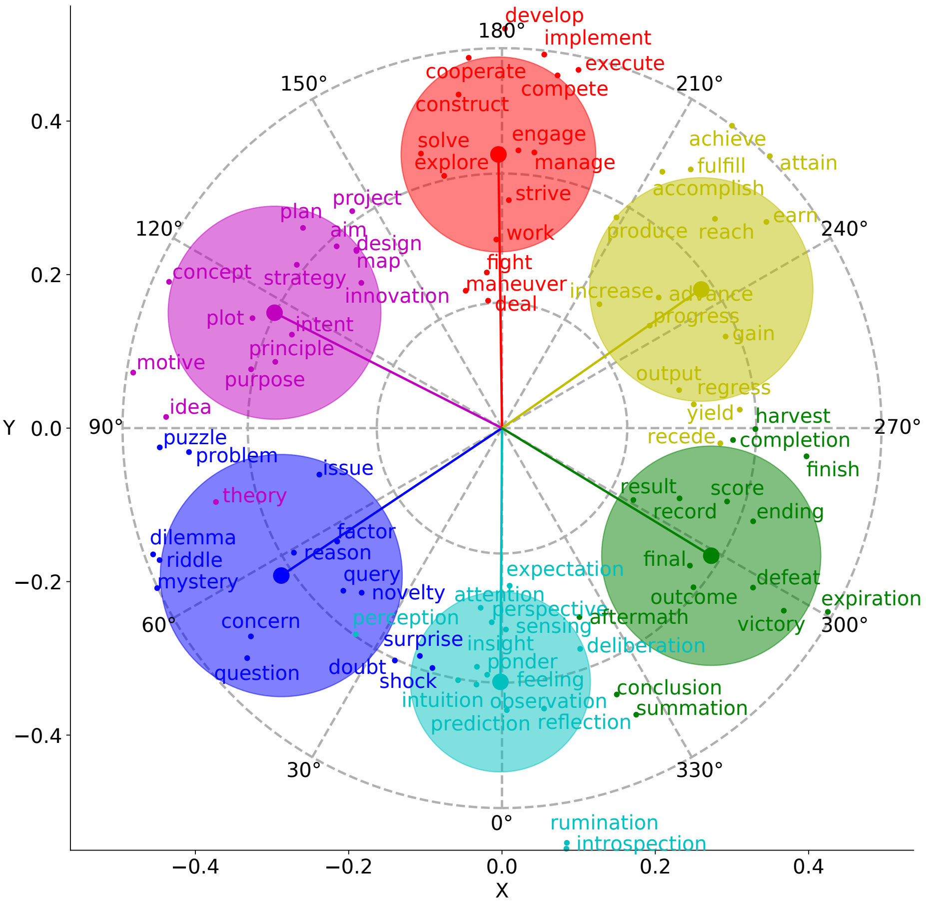

Figure 5: Mapping of the process terms listed in Table 1 to the process semantic plane $\vec{\Omega}_n$ identified in 300-dimensional word2vec space. Terms belonging to *Sensing*, *Novelty*, *Goal-Plan*, *Action*, *Progress*, and *Result* context classes are colored in cyan, blue, magenta, red, yellow, and green consistently with the above. Radii of color circles indicate coordinate variance of 1200 points within each context class as in Figures 5 and **??**. Mean scattering of individual terms around their center-prototype vectors $\vec{S}_k$ is 17° on average.

Scattering of individual terms In Figure 5, individual terms specific to each of six process-stage context classes *Sensing*, *Novelty*, *Plan*, *Action*, *Progress*, and *Result* are shown by cyan, blue, magenta, red, yellow, and green dots positioned in the XY plane by coordinates s_x and s_y found from (19). Large circles with radii $r_k = \sqrt{\mathrm{var}(s_x^k) + \mathrm{var}(s_y^k)}$ equal to 0.14 ± 0.01 reflect scattering of the terms in each context class.

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Mean-class semantic vectors In the same color notation, vectors $\vec{S}_k$ (21) are projections of mean word2vec prototypes $\vec{W}_i$ (20) to the (normalized) process semantic plane $\vec{\Omega}_{\mathrm{n}}$. Azimuthal phases of these vectors deviate from the ideal center-class positions by 3° on average. Together with nearly-identical lengths $|\vec{S}_k| = 0.33 \pm 0.01$ this indicates good agreement with the ideal symmetric scheme shown in Figure 4.

Phase-resolution quality measure Quality of process semantic map is measured by ability to correctly categorize an individual term based on its position in the angular dimension ϕ. This is quantified by standard angular deviation of individual terms ϕ_i^k from their center-class positions Φ_k

$$\Delta\phi = \frac{1}{6}\sum_{k=1}^{6}\sqrt{\frac{\sum_{i=1}^{N}\left(\phi_i^k - \Phi_k\right)^2}{N}}, \tag{23}$$

where $N = 15$ is the number of terms per context class. Reliable categorization requires $\Delta\phi$ to be less than half of angular distance between process stages

$$(\Phi_{k+1} - \Phi_k)/2 = 30°. \tag{24}$$

The map in Figure 5 with $\Delta\phi = 17°$ satisfies this condition as seen from non-overlapping scattering circles of the neighboring context classes. Tight layout of prototypes in Figure 5 supports choice of discretization of the process-semantic dimension motivated in Section 3.1.

4.3 Testing

Robustness and accuracy of semantic mapping procedure described in Section 4.2 was probed in the following tests.

4.3.1 Randomization

In this test, 90 terms listed in Table 1 were assigned to six context classes in random way. Word2vec representations in each of the obtained sets were averaged analogous to (20) to obtain six new prototypes $\vec{W}'_k$. The latter were used to find the process plane $\vec{\Omega}$ that would satisfy the phase requirement (21) in the same way as the original prototypes $\vec{W}_k$ (22). All 90 terms were then projected to this new plane.

As shown in Supplementary Material, randomization procedure degrades angular resolution (23) of the resulting map in drastic way. Thus, imposing the ideal azimuthal phases Φ_k to the representation vectors in (21) does not

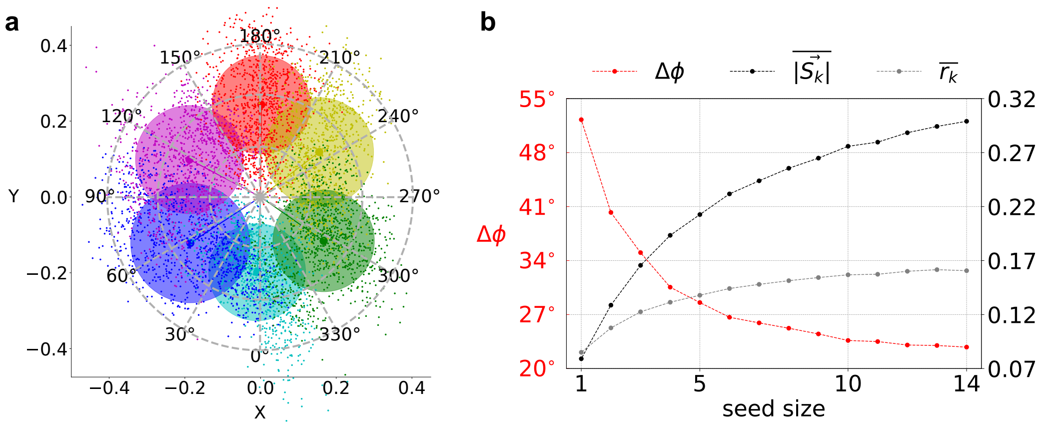

Figure 6: a: Mapping of $6 \times M \times (15 - N) = 6000$ terms based on semantic prototypes formed by $N = 5$ randomly selected «seed» terms, repeated for $M = 100$ times. Radii of color circles indicate coordinate variance of 1000 points within each context class as in Figures 5 and **??**. b: Standard angular deviation (23), mean amplitude $\overline{|\vec{S}_k|}$ and mean scattering radius $\overline{|R_k|}$ for different seed sizes N. Angular resolution threshold (23) is reached at $N = 5$ used in the left panel.

produce the expected semantic structure if the latter is not supported by regularities in source data. This constitutes statistically significant evidence for existing of the expected process-semantic regularities among single-word contexts within English language.

4.3.2 Mapping of novel terms

In this test, 15 terms populating each context class according to Table 1 were divided to N seed and $15 - N$ probe items. The process plane $\vec{\Omega}_{\rm n}$ was identified based on $6N$ seed terms, while the remaining $6(15 - N)$ probe terms were mapped to this plane by the procedure used above. With seed size $N = 3$, that is, three seed terms per semantic class randomly selected from Table 1, this procedure was repeated $M = 100$ times. The resulting scattering of $6M(15 - N) = 7200$ probe terms is shown in Figure 6(a).

For seed sizes N from 0 to 14, mean angular positions of $M(15 - N)$ points belonging to each context class agrees with the ideal values Φ_k as in Figure 6(a). Angular resolution of the map, as expected, depends on N. When semantic prototypes $\vec{W}_k$ are formed by randomly chosen $N = 1$ seed word each, the resulting map strongly depends on this random choice. This produces angular deviation (23) of 52° below the threshold (23) that is insufficient for reliable process-stage categorization of individual terms.

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Increasing of the seed size N suppresses this noise by virtue of more stable semantic prototypes (20). As shown in Figure 6(b), discrimination threshold (23) is reached near $N = 4$ when the mean scattering radius $\overline{|R_k|}$ drops below one half on the mean amplitude $\overline{|\vec{S}_k|}$. The map shown in Figure 6(a) is close to this borderline regime.

4.4 Relation to other semantic maps

4.4.1 Self-organized semantic map

The qubit semantic space discussed above is remarkably close to the self-organized semantic map (SSM) build from single-word synonym-antonym relations via physical minimum-energy principle Samsonovich & Ascoli (2010). First agreement is dimensionality of the map. In SSM it was not restricted apriori, but determined empirically to properly account for similarity relations. 95% of the corresponding data variance is found representable in three dimensions, with distribution of 15 thousands of individual word vectors similar to the Bloch ball shape polarized in Z dimension (Figures 1 and 2 in Samsonovich & Ascoli (2010)). Second, three main SSM dimensions closely match the meaning of the qubit's Cartesian axes described in Section 3.3. Valence (good-bad), arousal (calm-exciting), and freedom (open-closed) dimensions of SSM correspond to Z (evaluation), Y (activity) and X (potency) axes of the qubit semantic space.

4.4.2 Semantic structures of verb contexts

The above results also agree with semantic structures of verb contexts discovered via multidimensional scaling of similarity grouping Wolff & Song (2003) and multi-language grammatical regularities Croft & Poole (2008). In the latter case, basis of the obtained two-dimensional space is formed by tense and aspect dimensions corresponding to the X and Y axes of the process-semantic plane. Namely, Future/Past related contexts are maximally/minimally potent, while perfective/imperfective contexts are minimally/maximally active. In Wolff & Song (2003), the obtained clustering of verbs into cause, enable, and prevent functional types realizes the main process-semantic triad shown in Figure 3. In terms of the authors Croft & Poole (2008), Figures 4 and 5 show universal conceptual structure relating the clustered situation types in full agreement with quantum semantic description.

4.4.3 Towards context-sensitive semantics

For both of the above approaches to semantic mapping, quantum theory offers fundamental explanation for the topology and structure of human representational space, established earlier by purely empirical means. More importantly, quantum approach opens a prospect for going beyond average-stable semantics accounted by SSM Samsonovich & Ascoli (2010) and classical approaches Croft & Poole (2008); Gärdenfors (2014); Osgood (1952); Osgood et al. (1957), that is a limiting case of context-sensitive word meanings in particular usage contexts. In the quantum approach, contextual subjectivity of is not a side effect, but the very essence of semantics indicated in the Introduction Surov (2020). Efficiency of the quantum qubit structure for this kind of context-sensitive semantic modeling follows from fundamental reasons discussed in Section 5.

5 Machinery of meaning

In Section 3, process structure of semantics is introduced via year and day-night cycles mapped to azimuthal dimension of the Bloch sphere. Possibility of this mapping can be seen as following from the equivalence of classical oscillation and precession of spin-1/2, shown in Supplementary Material. However, physical essence of quantum dynamics is different from classical case. This difference, lying in the core of quantum mechanics, is that qubit state accounts for potential future of the system, rather than to its actual properties like position and momentum described by classical mechanics and logic Aerts (2010); Baltag & Smets (2011); Gabora & Aerts (2005); Jaeger (2012, 2017).

In semantics, this feature of quantum theory results in particular relations between uncertainty, process, and meaning described in this section. Quantum theory appears as a unique framework integrating these notions in strict quantitative terms. The concluding subsection 5.4 extends view of the qubit's geometry as an archetypal semantic structure pervading human cognition and culture as illustrated on several examples.

5.1 Uncertainty and Meaning

5.1.1 Task-oriented semantics

In the living nature, pragmatics of life limits allocation of scarce cognitive resources only to vital behavioral tasks to maximize probability of the desired events; from the start, meaning of cognitive and communicative symbols is

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determined by their practical use Glenberg (1997); Graben (2006); Greenberg & Harman (2009); Hadley (1989); Peirce (1997). Up to recent times, thinking of things out of direct survival value was a privilege of a few philosophers and scientists in the most prosperous societies. Even abstract philosophical thought, however, shapes the resulting theoretical paradigms, applied science and technology, eventually coming to the level of real decisions on the ground, irrespectively of whether this influence is realized or not.

Quantum model presented above subscribes for this pragmatic stance, so that meaning of a theory, idea, or any single factor reflected by human cognition is determined by how it contributes to resolution of a particular behavioral uncertainty. Recognition of this potentiality, the possibility of choice, on the background of reality is requisite for the very notion of meaning Frankl (1984); Sanz et al. (2012).

Consider for example the possibility to go fishing (1) or not (0). Then,

- presence of hunger is important because fish is eatable and therefore can be used to resolve the problem;
- the weather, season, and the daytime are important because they affect the biting;
- distance to the lake or river is important because it defines the travel's cost;
- trekking, seeking, camouflage, and other skills are important because the fish has to be found and outfoxed;
- the fishing method is important because the pike does not bite on the bread;
- facilities for accumulation, transportation, processing, and storage are needed because otherwise the product will go waste,

and so on. Meaning of the hunger, weather, distance, skills, methods, and facilities is created and defined by their subjective value for the considered decision.

5.1.2 Semantic relativity

As indicated in Section 4.1, meaning of the same context-factors can be different for different behavioral uncertainties; meaning of the `rain` for fishing is not the same as e.g. for haymaking. This semantic relativity is at the core of quantum semantics, where the very Hilbert space used for context representation is constructed on the basis of particular decision alternatives. Quantum semantics is thus fundamentally contextual in drastic contrast with classical approaches mentioned in Section 4.4.

Averaging over multiple bases destroys meaning of the most contexts, as in the `rain` example above. The remaining average-stable part (Section 4.1) is accounted by the classical notion of meaning considered as intrinsic property of contexts Osgood (1952). This objectified, absolute semantics is a limiting case of semantic relativity ingrained in the quantum approach. As in physics, this limit is achieved by averaging over «macroscopic» amount of individual usage cases as in the word2vec data used in Section 4.

5.2 Process and Meaning

5.2.1 Causality

Connection between process and meaning follows from the same pragmatic nature of human cognition referred to in Section 5.1; now, however, the essential aspect is that behavioral efficiency motivates cognition to work in causal-prognostic mode allowing for pro-active strategic behavior Barrett & Simmons (2015); Barsalou (2009); Behrens et al. (2007); Bubic et al. (2010); Connolly & van Deventer (2017); Craik (1943); Freeman (2008); Friston (2010); Kelly (2003); Pally (2007); Perrykkad et al. (2021). Tasks ranging from maintenance of single-cell allostasis to cross-national cosmic missions require from subjects reflection of causal if-then links between goals, events, and environmental factors. For successful outcome of the considered task, meaning of a particular factor or event then is determined by its function in multistage, goal-oriented causal chain of process stages. The process sequence then functions as a meaning-generating structure in cognition of a subject.

Exactly this approach is formalized in the quantum model of context representation. In the fishing example above, contextual factors are organized by the process-stage sequence shown in Figure 4. Stages of this structure are linked by causal relations so that each stage is allowed by the previous and necessary for the following one. Namely, hunger - *Novelty* - is only possible if perception, expectation, or prognosis took place at *Sensing* stage; subjective *Goal* regarding this novelty is the object of *Planning* stage taking into account weather, distance, time, and other factors. The plan allows for *Action*, *Progress*, and *Result* stages to which methods, skills, and facilities contexts are mapped.

In the above list, importance (i.e. subjective value – meaning) of each contextual factor is explained after beCAUSE flag, stressing the fundamental

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role of causality in human thought Chalmers (2011). The following part of each sentence refers to a particular fragment in the causal structure of the fishing process. In this manner, each represented factor is linked to others via the part-whole relations essential for semantic phenomena Stadler (2020).

In Whiteheadian terms, process-semantic representation of information corresponds to the type of perception called «causal efficacy», identified as fundamental mode of cognition in nature Chater & Oaksford (2013); Shalizi & Crutchfield (2001); Whitehead (1929); Young (2016). It opposes «presentation immediacy» denoting passive, abstract information unrelated to any subjective goal. This latter case corresponds to the object-based representation mode addressing actual, static states of nature, where objects are related by correlation instead of causality Bareinboim & Pearl (2016); Pearl (2000); Pearl & Mackenzie (2018). In the above experiment, raw word2vec data $\vec{W}_k$ are of «presentation immediacy» type, while vectors $\vec{S}_k$ shown in Figure 5 are their (average-stable) causal-semantic counterparts (cf. semantic pointers of Crawford et al. (2016)).

5.2.2 Objective restrictions on semantic subjectivity

As indicated in Section 2.3.1, process-semantic representation is subjective in nature. Meaning of the same information is different for different subjects, so that semantic relativity discussed above includes subject-to-subject variation Kelly (2005). In the same example, for someone who knows nothing about fishing, feeling of hunger has no relation with the `fish`, `lake`, and other contexts mentioned above. Alternatively, a subject might try to get a salmon from a water well if his personal theory predicts this possibility.

The latter example shows that subjective causal structures can be both correct and incorrect. Faulty theories ignoring objective causality decrease efficiency of behavior, providing a feedback for the learning process van Ments & Treur (2021). An experienced fisherman, as any other professional, is bound to respect regularities of nature involved in his activity. The latter restrict subjective cognitions to a limited range of objectively efficient process-semantic causal structures.

5.3 Process and Uncertainty

5.3.1 Unifying quantum structure

As follows from Section 5.1, meaningful information necessarily refers to a particular decision alternative with (objectively) observable outcomes. Taken alone, the process-based representation discussed in Section 5.2 therefore does not make sense out of data; to be meaningful, it should be supplemented with a dimension encoding value of information for the target decision alternative. This is achieved by vertical (θ, Z) dimension of the qubit semantic space. Although represented by orthogonal spherical coordinates, objective and subjective aspects of meaning (Section 2.3.1) are therefore inseparable; linear and circular dimensions of qubit state space carry semantics only in pair.

Geometry of the qubit semantic space thereby establishes relation between process and uncertainty – two fundamental concepts of natural science. This relation is seen right in Figure 1, where diameter of the Bloch sphere represents classical Kolmogorovian probability space of binary uncertainty Kolmogorov (1956); equator of the sphere represents (virtual) oscillatory process subjectively associated with the basis distinction, as envisioned in Kauffman & Varela (1980). Qubit representation space thus can be seen as development of circumplex models of cognition Bezembinder & Jeurissen (2003); Fabrigar et al. (1997); Nagy et al. (2019); Tracey (2000), capturing the process aspect of semantics.

5.3.2 Neural substrate

Qubit representation of contexts has similarity with the neural-based model of intellectual operations Sokolov (2001a,b). Akin to the latter, qubit representation of contexts can be seen as universal mechanism encoding excitation of the corresponding neuronal ensembles as vectors within interpretable spherical space. Points in the Bloch ball then map to the surface of a four-dimensional hypersphere considered by Sokolov.

Via this mapping, quantum approach accompanies model Sokolov (2001a,b) with semantic perspective explicated in this Section, cf. Vartanov (2011). Specific encodings for actual and potential types of information, distinguished in the quantum approach and further discussed in the Section 6.2, are observed on the neurophysiological level Abe & Lee (2011) in the Rock-Paper-Scissors game. In agreement with Section 2.3.2, the latter exemplifies minimal three-context setup requiring context-sensitive cognition Basieva et al. (2019); Falk et al. (2021).

Oscillatory dynamics Via oscillatory dynamics of neural excitation modes, harmonic oscillation forming process-based azimuthal dimensions of qubit is also at work in human cognition itself Armstrong et al. (2018); Arnal & Giraud (2012); Aur (2012); Bastos et al. (2012); Başar (1998); Hobson & McCarley (1977); Hutcheon & Yarom (2000); Neuling et al. (2012); Niebur et al. (1993). Namely, recall (1) or no-recall (0) of an idea, thought, or concept

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responsible for the considered behavioral observable Bruza et al. (2008); Gabora et al. (2008) corresponds to potential activation of a neuronal mode corresponding to this cognitive entity Damasio (1989); Fernandino et al. (2015); Kak (1996); Pribram (1971). Phase of the neural oscillation, in turn, encodes relations between the contexts Acacio de Barros & Suppes (2009); Fries (2015); Suppes et al. (2012); Ten Oever et al. (2020); Tiesinga & Sejnowski (2010); VanRullen & Dubois (2011) quantified by azimuthal angle of the qubit semantic space.

By supporting standard wave phenomena including superposition and interference Orefice et al. (2009), neural oscillatory dynamics is thus capable of carrying process- and meaning-based cognition discussed above. Smooth account of psycho-physical parallelism further supports quantum approach to cognitive-semantic modeling Khrennikov & Asano (2020); Khrennikov et al. (2018); Surov et al. (2021).

5.4 Archetype of meaning

As a fundamental template of human cognition, qubit semantic space has properties of Jungian archetype Frye (1957); Jung (2014). Though Jung was aware of cyclical processes of nature ingrained in human mythology and psyche, his list of archetypes (Anima, Animus, Hero, Enemy, Wiseman, etc.) only contains static entities. By virtue of its process aspect, qubit semantic structure extends classical notion of the archetype to the dynamical realm.

5.4.1 Archetypal qualities of the qubit semantic structure

Qubit semantic structure has the following distinguishing features of classical archetype:

1. Empty-form universality
   Archetypes are empty forms filled by situation-specific content in each individual life, remaining useful in different circumstances across epochs. This agrees with the function of qubit semantic structure applicable to any binary decision, not even necessarily human: adequate reflection of the goal-related factors enabling correct behavioral prognosis is beneficial to any individual.

2. Unconscious nature
   This basic quality of archetypes explains robustness and speed of their operation by impossibility of conscious control. Archetypes are not consciously learned or individually invented, but inherited from the

ancestors as hard-wired cognitive patterns. In the case of qubit semantic structure grounded in oscillatory neurodynamics, this property is taken to the extreme, since cognition in other anatomical basis would amount to inventing a different form of life. In this respect, qubit semantic structure is more fundamental than social- and personality-relevant archetypes.

3. Simple and intuitive
   By virtue of unconscious basis, archetypes have simple and intuitive use. On conscious level, they are easily understood e.g. as folk tale characters and their roles Booker (2004). Similarly, simplicity of the qubit semantic structure stems from the basic regularities of nature it reflects Piantadosi (2020). Binary alternative 1-0 abstracts basic duality of human nature exemplified by oppositions of good-bad, up-down, do-not do, etc. Circular dimension is easily grasped from ubiquitous oscillatory processes observed in daily life; this is the basic «causal topology» Chalmers (2011), an innate «theory of causality», explaining ease of causal learning and thinking Goodman et al. (2011), Section 5.2.1. In particular, azimuthal phase ϕ of the qubit semantic space literally corresponds to the *phase* of a (virtual) context-organizing process, as it would be said in plain non-scientific English and Russian.

4. Geometrical expression
   Empty-form universality mentioned above is conveniently expressed in geometric form, establishing relations between abstract elements that are instantiated only in each particular case. Such archetypal schemes called mandalas, reflecting traditional views of nature, are known in big variety Brauen (2009)[4]. Qubit semantic structure operates in similar way. This paper essentially expounds a single stereometric mandala shown in Figure 1, visualizing innate human structure for representation of semantics Zhuge (2010).

Dynamical nature of the qubit semantics complements classical archetypes of static kind. Akin to thematic/semantic roles Feldman et al. (2020); Rissman & Majid (2019); Schank & Abelson (1977), the latter facilitate fragmentary recognition tasks, while the process-causal relations between them

[4]Description «The mandala principle is connected with a learning process or a practicing process. The Tibetan word for mandala is kyilkhor. Kyil means "center", "khor" means "fringe", "gestalt", "area around". It is a way of looking at situations in terms of relativity» (Trungpa, 2011, ch.1,2) closely aligns with quantum semantic terms. According to Jung, mandala represents «nuclear atom» of human psyche (Jung, 1964, p.213). Planar layout typical to traditional mandalas is obtained as two-dimensional projections or sections of the Bloch sphere akin to the process-semantic structure shown in Figure 4.

are accounted by process dimension of the qubit semantic structure. This process-based embedding does not override innate representations for objects, actions, and places Gärdenfors (2014), but integrates them even across object-specific domains of experience (Carey, 2009, ch.6). With Lakoff's invariance hypothesis Lakoff (1990) extended to the process domain, models for analogy and metaphoric cognition Gentner (1983); Gibbs (1992); Lakoff & Johnsen (2003); McGregor et al. (2019) gain additional explanatory power via the principle of dynamical similitude Amazeen (2018).

5.4.2 Examples

Story structure As any archetype, qubit semantic structure pervades human culture. However, contrary to static archetypes, it can not be recognized in discrete characters, situations, and events. Rather, process aspect of the qubit semantic space shapes the narrative in fiction, movies, and artwork. In particular, classical set of screenplay acts

Setup - Development/Confrontation - Resolution

Field (2005); Seger (2010) reflect the basic triad of process stages shown in Figure 3(a). Further discretization, limited by capacities of human attention as mentioned in Section 3.1, is done in many ways Brütsch (2015). The difference between alternative approaches is illustrated by six- and seven-stage categorizations

Introduction of setting and characters - Explanation of a state of affairs - Complicating action - Ensuing events - Outcome - Ending Bordwell (1985),

Weakness and Need - Desire - Opponent - Plan - Battle - Self-revelation - New equilibrium Truby (2008),

both of which map to the process semantic structure shown in Figure 4 in obvious way.

Organizing contexts according to this system amounts to narrative-based representation of the world Akimoto (2021); León (2016) as manifested in stories from ancient myths to present-day movies Booker (2004); Truby (2008); four types of mythos, namely

Comedy - Romance - Tragedy - Irony/satire,

map to four seasons of the year, each further represented by sequence of six phases Frye (1957), (Lucas, 2018, ch.2). Distilled form of this «dramatic code» is seen in scientific writing, where navigation in the process semantic dimension is facilitated by paper structure.

In metaphorical manner, the archetypal story structure translates from the journey of a fairytale's hero to the «archetypal customer journey» addressed by significant sector of data science van der Aalst (2016). In this view, the classical product life-cycle curve Cao & Folan (2012) is projection of the circular phase-plane process trajectory to the activity dimension.

Control loops and system science The process-semantic archetype underlies the life cycle of complex systems including human individual Dufour et al. (2018); Frye (1957); Hurst & Zimmerman (1994); Ohlsson (2011). Accordingly, experience, decision making Kelly (2005), pragmatism Sowa (2015), learning Ohlsson (2011), creativity Wagenmakers et al. (2018), sleep Hobson & McCarley (1977), behavior change Duckworth & Gross (2020), industrial quality control Johnson (2002); Moen & Norman (2010), and research Hevner Alan (2007); Yanai & Lercher (2019, 2020) cycles reflect the same circular semantic structure discretized in up to five stages.

Universality of this structure motivates its integration in cybernetic control loops. An example is sequence Sanz et al. (2012)

Collect – Integrate – Anticipate – Decide - Act,

in other approach coarse-grained to the basic

Sense - Think - Act

triad in various wordings Chatman & Flynn (2005); Hoffman & Prakash (2014); Kelly (2003); Petschnigg et al. (2019).

6 Outlook

As noted in the Introduction, this paper expands boundaries of the classical approach to cognitive modeling to access subjective dimension of meaning. This section provides a broader perspective of the achieved result facilitating further steps in this novel terrain. Section 6.1 outlines methodological difference between classical and quantum approaches to semantic modeling. Section 6.2 discusses practical implications of this difference.

6.1 Methodological perspective

Methodological content of quantum process semantics is revealed by considering it from object- and process-based perspectives Galton & Mizoguchi (2009); Rescher (1996); Sowa (2000).

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Object philosophy Object philosophy sees the universe as composed of discrete entities, whereas processes are derivative notions labeling motion of entities in space. Ascending to ancient Greece and Egypt Schrödinger (1954), this philosophy epitomized in Newtonian and statistical mechanics. In both, nature is a set of inert bodies, or particles, interacting by contact forces; following deterministic laws, ensembles of particles are defined by positions, velocities, masses, pressures, and temperatures. Existing independently of measurement procedures, the latter exemplify static, objective quantities constituting classical description of nature. As illustrated by classical part of natural sciences, this approach effectively reveals quantitative regularities of inert matter.

Process philosophy Process philosophy, in contrast, comprehends nature in terms of continuous dynamics of transformation and change embodied by substances and objects, specification of which is of secondary importance Shaviro (2014); Whitehead (1929). This view of nature, preferred in non-European cultures Harrison (2013); Maffie (2013), is suitable to discover qualitative regularities of the living Nicholson & Dupre (2018). Theories of human nature and the associated practice systems developed in the East constitute humanitarian science and technology parallel to their «hard» counterparts of Western kind.

Integrative quantum view Quantum process semantics incorporates both object- and process-based views of nature. As indicated in Section 5.3.1, one side of the quantum model is an objective behavioral uncertainty bound to end in one of several alternative states; result of this experiment will be recorded in the environment, becoming objective property of nature verifiable by subject-independent measurement procedures. The choice, however, relies on the process-based logic of a subject representing the decision context not as actual thing in itself, but by relation to the potential future and other contexts via subjectively constructed virtual process. The two kinds of philosophy capture objective and subjective aspects of quantum semantics described in Section 2.3.1, cf. Mugur-Schächter (2002).

Account of both objective and subjective aspects of nature[5] explains universality of quantum theory valid both or inert particles and living organisms Aerts (1995); Atmanspacher et al. (2002); Auffray & Nottale (2008); Khrennikov (2010); Mugur-Schächter (1993); Nottale & Auffray (2008); Peres & Zurek (1982); Wendt (2015). Methodology of quantum behavioral-semantic

[5]Their coexistence in quantum phenomena was first identified as wave-particle duality Jaeger (2017), also understood as contextual phenomenon Falk et al. (2021).

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Table 2: Properties of objective and subjective aspects of information. Meaning arises from combination of the two, where subjective process structure is used to organize contexts in relation to objective behavioral alternative. Corresponding mathematical structure is qubit state visualized in Figure 1.

	Objective information	Subjective information
Domain	Actuality	Potentiality
Basic objects	Event, Particle, Set	Process, Wave, Field
Value	Absolute, non-contextual	Relative, contextual
Topology	Linear $0-1$	Circular $0-2\pi$
Spherical coordinate	Polar angle θ	Azimuthal phase ϕ
Number system	Real $\mathbb{R}$, scalar	Complex $\mathbb{C}$, vector
Basis elements	Two	Three
Regularity	Correlation	Causality

modeling does not need this distinction Surov (2020); dropping of any of the two complementary aspects produces largely incompatible, marginal object- and subject-based worldviews of limited applicability Galton & Mizoguchi (2009) realized e.g. in classical physics and naive psychology Wellman & Gelman (1992). The former, objective «view from nowhere» description Nagel (1986) appears as a limiting case of subjective embodied cognition involved in active sense-making Clark (2019); Cosmelli & Ibáñez (2008); De Jesus (2018); Glenberg (1997); Pinker (2008); Wilson (2002), accounted by the developed model.

6.2 Practical perspective

Object- and process-based descriptions of nature involve specific types of information compared in Table 2.

6.2.1 Classical-objective informatics

Contemporary informatics embodies the mindset underlying natural science of 17-19 centuries. Its keystone element, the bit, represents dichotomic alternative in which 1 indicates presence of a particle, force, electric current etc, and 0 labels absence thereof (or vice versa). This is objective property of nature endorsed by the classical worldview; it is changed neither by composition of multiple bits, nor by subjective uncertainty about actual state of the bit represented by Kolmogorovian probability Kolmogorov (1956).

As indicated in Section 6.1, objective information is appropriate to record actual states of nature Gärdenfors (2020); Kemp (2012), including objects and features like positions of bodies, velocities, mechanical forces, and other well-defined quantities (Whitehead, 1929, p.169), called by Einstein «elements of physical reality» Einstein et al. (1935); Khrennikov (2017); word2vec data $\vec{w}_i^k$ (20) (as well as other high-dimensional semantic representations Günther et al. (2019)) comprising averaged, decontextualized statistics of the words' use, are of this type. Information of this «presentation immediacy», objective kind, appropriate to simulate behavior of inert systems, dominates modern information technologies.

Limitations However, as mentioned in the Introduction, when applied to the living, non-predetermined behavior, objectivist simulation runs aground Kaehr (2017). The reason (Section 5.2) is that always subjective natural cognition, by design oriented towards causal-prognostic modeling of behavior, works both with actual (context-independent) and potential (context-dependent) domains of nature. Accordingly, limiting the simulation to objective information is insufficient; it should be supplemented with subjective counterpart operating in the process representation mode Rowe (2005).

6.2.2 Quantum-semantic informatics

As indicated in Table 2, account of subjectivity, necessary to surpass limitations of classical-objective informatics, is possible by supplementing classical bits with circular phase dimension. Figure 1 shows quantum-theoretic implementation of this procedure. Mathematically, it is formalized by going from real to complex-valued calculus as envisioned by Kauffman & Varela (1980); Scharff & Cooper (2005). In logical terms Poole (1997); Sloman & Hagmayer (2006), this corresponds to generalization from between classical-Boolean and quantum logic of decision making Bruza & Cole (2005); Khrennikov (2015), formulated as transition from set-based (classical Kolmogorovian) to (Hilbert) space-based (quantum) probability calculus Blass & Gurevich (2008); Khrennikov (2009).

Transition to the novel type of information is naturally achieved in quantum computing, where electrons' spins, photons' polarizations and other spin-1/2 systems are encoded in qubit states (1), while processing is realized by the laws of atom-scale physics Jaeger (2019); Nielsen & Chuang (2010). As indicated above, this encoding accounts for potential states of the future that are intrinsically context-sensitive Jaeger (2012). The achieved «quantum supremacy» essentially results from this contextual information type Amaral (2019); Howard et al. (2014); Khrennikov (2021) supporting a broader class of algorithms Bharti et al. (2020); Dunjko & Briegel (2018); Ying (2010).

Quantum algorithms on classical hardware Physical implementation of quantum logic in human cognition is still under discussion, with considered possibilities including quantum biomolecular processes in neurons Hameroff & Penrose (2014); Jedlicka (2017), equivalent neural-network circuits Busemeyer et al. (2017); Selesnick & Piccinini (2018), and mechanisms mentioned in Section 5.3.2. This uncertainty, however, does not interfere with methodology quantum cognitive modeling: as befits abstract information-level algorithmic description, this approach works well without specification of a hardware. Similarly to computer simulation of quantum phenomena routinely done in physics, quantum cognitive modeling is based on complex-valued linear algebra tractable by any laptop Abraham (2019); Johansson et al. (2013). Quantum-inspired algorithms implemented on classical hardware are the essence of quantum models of cognition and behavior mentioned in the Introduction.

Is Hilbert-space linear algebra «quantum» in nature? Not at all. It can be used with no reference to quantum theory altogether; the regularities discovered in quantum cognition could be found by blind search or automated discovery methods Alhousseini et al. (2019); Iten et al. (2020). Quantum approach to cognitive modeling simply takes advantage of mathematical structure better aligned with the nature of human cognition Longo (2003), further facilitated by solid conceptual structure of quantum theory. The latter merely serves as an algorithm developer's guide suggesting solutions and methods Manju & Nigam (2014); Montiel Ross (2020); Surov et al. (2021). This is another kind of the «quantum speedup» hardly suitable for quantification.

Towards semantic information science Quantum-semantic modeling compatible with classical computation hardware is not limited to elementary tasks considered above. As the concept of material atom opened the door for countless phenomena of physics, quantum-theoretic qubit structure is the key for process-semantic domain of nature.

The latter is already addressed by management-, workflow-, transaction-, organization-, life-, and other cycle-type models of the process-aware information systems Dumas et al. (2005); Grambow et al. (2017). Here, quantum approach establishes close relation between semantics and process mining technologies van der Aalst & Al. (2012); van der Aalst (2011); Augusto et al. (2019); Davis & Altmann (2021); Guarino (2017); Koorn et al. (2020); Santipuri et al. (2017); Van der Aalst (2016); Zhao et al. (2018), contributing to the development of explainable artificial intelligence and data science Adadi & Berrada (2018); Chou et al. (2021); Gal & Senderovich (2020); Lipton (2018); Miller (2019); Roscher et al. (2020); Rudin (2019).

In the broader field of cognitive modeling, quantum process semantics provides the predictive-dynamical, causal approaches Clark (2013); van Gelder (1998); Gładziejewski (2016); Kelly (2005); Miller et al. (1960); Schank & Abelson (1977) with mathematically formalized representation structure - the qubit. Quantitative modeling of human subjectivity sketched above opens novel prospects for the next-generation cybernetics and semantic information science Samsonovich et al. (2009); Widdows & Bruza (2007).

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