TRACE INSTITUTE

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A Science of Reality:
Observers, Interfaces, and Traces

Abstract

Observation is the foundation of science, informing the construction, confirmation, and disconfirmation of scientific theories. Observers may use measuring devices, but ultimately their minds must interface with the physical world. Unfortunately, science has no coherent account of observation. The goal of the Trace Institute is to develop a mathematical framework for observation, and to reformulate scientific theories in light of this account. Here, we propose the recursive trace logic, where observation is fundamental. Spacetime comprises an observer's interface and traces of the universe beyond it are perceptible. We will explore the recursive trace logic to derive spacetime physics and other natural sciences from an observer's perspective. This science of reality will enable unprecedented technologies and contribute to the next phase of civilization.

1 Introduction

In the fleeting development of human civilization, modern science is undoubtedly among the most impressive achievements of *Homo sapiens*, alongside the harnessing of fire, invention of the wheel, and the evolution of agriculture and cities. Science is the systematic organization of the fundamental objective of human intellectual inquiry: to decipher the nature of the universe and our position in the cosmos. In following this course, cumulative insights and technological breakthroughs from scientific research became a powerful engine of modern society.

The twin philosophical pillars of science over the last few centuries have been materialism and reductionism, which together form a discrete epistemology, materialist reductionism, positing that nature can be understood – and only understood – by identifying and studying microscopic material components and their macroscopic physical observables. In this framework, nature is no more and no less than a material spacetime machine, like a watch, whose ultimate proof is the prediction of larger components by the mapping and manipulation of smaller components.

From research on atomic structure to the weather and the brain, materialist reductionism drives the rational development of new predictive capabilities that have undeniably transformed society. In consequence, there is a tacit assumption that materialist reductionism will eventually explain the universe *in toto*. How accurate is this assumption? Not very, actually. Despite centuries of advances, science has not solved the most fundamental problem of human existence: how to reconcile the seemingly objective structure of the world with the reality of our own subjective experience.

Ironically, the root of this problem lies with epistemic limitations of materialist reductionism, which may be contrasted with more holistic approaches, like phenomenology, which center experience as fundamental to an accurate description of the universe. Modern science and philosophy have failed to untangle the Gordian knot of reality, typically

retreating to a dualistic metaphysical posturing that by definition cannot solve the problem. Yet, a commitment to either a fundamentally material or a fully conscious universe is not required. Here, we introduce a work-in-progress mathematical framework called the trace logic for building the infrastructure of a non-dual science of reality. We review the mathematical theory to date, and its potential technological applications.

2 The Observer and the Interface

A long-standing paradox of science is that a universal theory of nature requires a formal understanding of the observer and of observation, but no current theory has attempted to rigorously include either. However, without a theory of observation, physics risks losing the very epistemic foundations on which it rests.

Physics has a history of acknowledging the observer in a limited perspective. Einstein's theories of relativity do consider the observer but they identify it as a mere frame of reference, a system of coordinates and clocks. In quantum theory, observation is an important aspect, but its nature is left undefined in an attempt to maintain an objective description of the world. In contrast, the physicist John Wheeler sought to designate an explicit role for the observer in physical reality. He coined the notion of a "participator" (Wheeler, 1990): an agent that observes the universe and participates in its creation. His "it from bit" doctrine proposed the physical universe is informational, which raises a crucial question: information about what, and for whom?

We assert that any theoretical framework for an observer who can experience a physical universe depends on the concept of an interface. The interface defines the membrane between an observer's experience and its reality, which is mathematically made precise in the Interface Theory of Perception (ITP; Hoffman et al., 2015). The theory is guided by the "fitness-beats-truth" theorem (Prakash et al., 2021), which shows that evolutionary pressure shapes perception to avoid veridical representation of observer-independent structure. Instead, perception's task is to provide a fitness-enhancing interface relevant to survival and reproduction. This is true for humans, but it is also true for non-human observers. In all cases, the interface defines the limitations of the observer and is therefore key to a theory of observation.

It is useful to consider a metaphor. Compare the icons on a computer desktop with the processes inside the computer itself (Hoffman, 2019). What is "really" going on in most computers is that charges are being moved across potential gaps in semiconductors in ways that affect the states of the processor and memory. What the user interacts with, the icons on the computer's desktop, has a lawful relationship with these operations, but the details of the underlying processes are not discernible from the properties of the icons themselves. Indeed, without external information it would be impossible to determine what physical, or virtual, substrate the computer is instantiated on.

ITP proposes that perception stands in a similar relationship to reality. The computer interface shows us what an observer needs to see in order to take actions that produce social or other forms of fitness, such as sending important emails, while hiding the complexity and physical instantiation of the underlying computational processes. Likewise, perceptual experience consists of those icons required for fitness-relevant interactions with reality, while concealing the structure of the underlying processes themselves.

Within theoretical physics, it has been frequently suggested that even the very notion of spacetime might not be fundamentally real, to be replaced by some deeper principles (Maldacena, 1999; Arkani-Hamed et al., 2025). We add to these that spacetime is best viewed as an adaptive interface, and the reality that we have direct access to is not the

objective world itself, but the experience mediated by that interface. Rather than rejecting physics, we seek to improve it. Its current foundations lack a formal theory of observation, and we seek to model the properties and dynamics of one or many observers.

3 Basic Trace Logic

The trace logic theory starts with modeling[1] a phenomenological process as a measurable space $(X, \mathcal{X})$, whose points $x \in X$ represent potential conscious experiences, together with a Markov kernel

$$\mathbf{Q} : X \times \mathcal{X} \to [0, 1].$$

Here X is the set of experiences and the collection of events of interest is described by $\mathcal{X}$. Then, for each $x \in X$, the map $\mathbf{Q}(x, \cdot)$ defines a probability measure on $(X, \mathcal{X})$ the collection of events described by $\mathcal{X}$. Together, the measurable space $(X, \mathcal{X})$ and the kernel $\mathbf{Q}$ define a Markov process in discrete time. In the special case where the state space X is discrete, the kernel $\mathbf{Q}$ can be represented as a stochastic matrix. In this case, for states $x, x' \in X$, the quantity $\mathbf{Q}(x, x')$ gives the probability that the next state of the process is x', conditional on the current state being x.

Markov processes are mathematically well understood and possess a number of useful structural properties. They are also general enough for our purposes, minimal, computationally universal, and straightforward to work with. For example, again in the discrete case, if we let $\mathbf{x}_t$ denote the probability distribution over experiential states at time t, then the distribution at the next time step is given by

$$\mathbf{x}_{t+1} = \mathbf{x}_t \mathbf{Q},$$

where we adopt the convention that probability distributions are represented as row vectors. Thus, after n time steps,

$$\mathbf{x}_{t+n} = \mathbf{x}_t \mathbf{Q}^n.$$

We discuss additional useful properties of Markov processes, including the existence of trace logic constructions, below. Note that while we consider simple cases here for illustration purposes, the proposed formalism can handle much more complex cases, such as continuous time and/or state spaces, as well as time dependent Markov kernels.

Finally, we introduce an integer $n \in N$ that serves as a book-keeping device for counting kernel executions. Many results, especially where they are related to physical laws, are derived for limiting cases where $n \to \infty$.[2]

Altogether, a phenomenological process can be written as

$$C = \langle (X, \mathcal{X}), \mathbf{Q}, n \rangle,$$

[1] The following section outlines a streamlined and condensed formalism, synthesized from several recent publications on "conscious agent theory," most notably Fusions of Consciousness (Hoffman et al., 2023) and Traces of Consciousness (Hoffman et al., 2024). The foundational framework established by (Hoffman and Prakash, 2014) remains entirely consistent with this current iteration and can be retrieved as a sufficiently decomposed variant. Earlier formulations explicitly stipulated the roles of actions and world states, predicated on the hypothesis that the dynamics of consciousness can be decomposed into distinct internal ("decision") and external ("perception-action") aspects. While these assumptions provide a natural heuristic, the present formalism adopts a more cautious stance regarding the decomposability of kernels and state spaces into respective internal and external constituents, analogous to the limits placed on the decomposability of Hilbert space in quantum theory.

[2] This follows a standard approach in field theory and complexity science that looks at asymptotic behavior. It should be distinguished from another important limiting behavior, namely that of large ensembles of many (interacting or free) particles. The latter is how most researchers think of consciousness (i.e. consciousness as an emergent property of many "neural particles").

see also Fig. 1. Equipped with these ingredients, we can explore the hypothesis that seemingly objective as well as subjective aspects of reality emerge from relations between potential states of conscious experiences, i.e. from structures defined on the state space $(X, \mathcal{X})$.

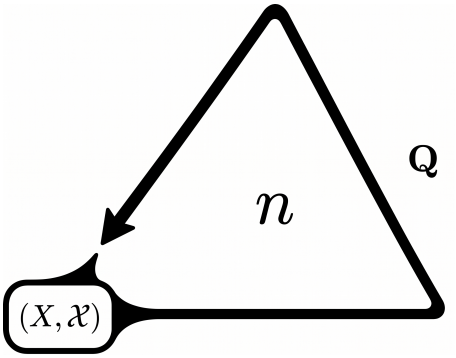


Figure 1: The Basic Architecture of Experience. The loop-like structure defined by the kernel **Q** starts and ends with conscious experience, consisting of a raw potential X and a collection of events $\mathcal{X}$. **Q** is stipulated to recover all aspects of an agent's internal cognitive mechanisms and its interaction with the world.

We now need to show how (i) all theoretical and empirical structures of physical science and (ii) the specific contents of any instance of subjective experience, such as the experience of a human being, can be accounted for in the theory. This naturally leads back to ITP that maintains that percepts are best thought of as an interface that motivates fitness-enhancing behavior. In agreement with this, the structure of our perception is generically not homomorphic to any objective structure of the environment (Prakash et al., 2020). From this perspective, the mathematical model is not so much about veridically representing what objectively exists "beyond" the interface, but about describing how we build up interfaces.[3] Thus, in this picture, familiar concepts from science, such as "spacetime," "matter," "energy," or "information", are viewed as (evolutionarily) convenient interface representations. The same is true for standard phenomenological notions such as "self" or "time-consciousness."

A central step in decoding the interface was taken by reformulating the trace chain theorem (Revuz, 1984; Hoffman et al., 2024): Let **Q** be a Markov kernel on a finite state space (which is potentially partially hidden). For any subset A[4] of the state space, there exists a unique Markovian kernel, $\mathbf{Q}_A$, which is called the "trace kernel" of **Q** on A, and is given by:

$$\mathbf{Q}_A = I_A \mathbf{Q} \left[\sum_{k=0}^{\infty} (I_U \mathbf{Q})^k I_A \right] = I_A \left[\sum_{k=0}^{\infty} (I_U \mathbf{Q})^k \right] \mathbf{Q} I_A,$$

where I_A and I_U represent multiplication by the indicator functions on the subsets A and U, respectively (U is the complement of A in the finite and discrete space X). This formula allows us to define a Markov chain, for any starting measure that is supported within A with $\mathbf{Q}_A$ as its kernel. Such a chain will stay within A: we refer to it as the "trace chain" on A.

[3] Philosophically, this would correspond to a radically "transcendental" move where metaphysics is no longer seen as a "dogmatic" project of rationalizing an unobservable entity outside of our experiential access (as it was practiced throughout much of history), but as a project to make transparent how a vast potential for consciousness is probed by us in concrete acts of subjective experience.

[4] We assume a discrete sigma algebra in both cases, i.e. $\mathcal{X} = 2^X$ and $\mathcal{A} = 2^A$, respectively.

If we restrict attention to the subspace A, we could then derive a "projection" as

$$q_A := a + b\left[\sum_{k=0}^{\infty} c^k\right] d,$$

see also Fig. 2.

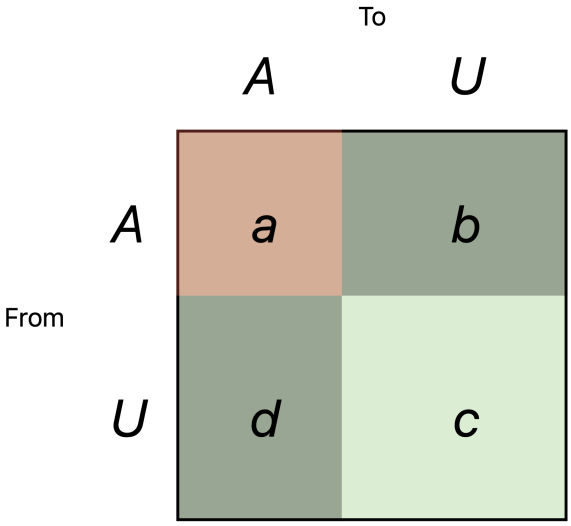


Figure 2: Geometry of the Trace Chain. Shown are the basic components of the matrix representation of $\mathbf{Q}$ according to a partition into visible and invisible subsets, A and U, respectively.

The trace kernel characterizes the effective dynamics on A as perceived by an observer who restricts attention to the subset A of X. Generally, the dynamics as it is perceived through A does not give any information about the underlying dynamics induced by $\mathbf{Q}$ on the whole state space X. The information about unobserved states is simply lost. While only a specific set of larger kernels are valid precursors to a particular trace, any given trace kernel could have been derived from an infinite number of larger, higher-dimensional kernels. Furthermore, tracing induces a partial order, wherein a kernel $\mathbf{Q}_1$ is said to be a trace of $\mathbf{Q}_2$ if the former can be derived from the latter via the construction above. Formally, then, $\mathbf{Q}_1 \leq \mathbf{Q}_2$. Crucially, as per the definition of a partial order, not all kernels are comparable: while some kernels may be ordered relative to one another, many pairs are strictly incomparable, and no universal order exists that holds for all kernels across the entire set of possible observations. Like any any partial order this one induces a logic; we can define properties like meets and joins (comparable to "ands" and "ors"), when they exist. The logic that the particular partial order described here induces is not globally Boolean though it contains local Boolean sub-logics. In summary, we define the trace logic as the structure that emerges as a consequence of restricting attention to a subset of the state-space of a Markov process (Hoffman et al., 2024).[5]

[5]The trace logic has been proven to be homomorphic to the Lebesgue logic of probabilistic belief (Hoffman et al., 2024), which has previously been identified as the logical principle behind a unified theory of perception, termed "observer mechanics" (Bennett et al., 1989).

4 Recursive Trace Logic

From the trace logic, we then define the recursive trace logic (RTL) as a proposed model of how perception emerges along with spacetime and its contents. In brief, the model can be viewed as an extension of the basic model described in Section 3, where in addition to the Markov kernel governing the transitions in the space of experiences there is also a hierarchy of Markov kernels governing changes to the state space itself.

We give a concrete example of a model with two levels. In this situation at any time step, the process can either utilize the current transition kernel on the current state space and make a transition, or it can take a "step up" in the hierarchy, and change the size and content of the state space. The state space changes are governed by a Markov kernel defined on the set of states available as restrictions and expansions of the current state according to the trace logic as well as some choice rules related to the state space expansions. We call this second level of the hierarchy the Policy Level as it defines policies for state space changes. It is easy to see how this can then be extended to further hierarchical layers, with a three level model including a Meta-policy Level, which includes a Markov kernel defined over possible policies, and so on to any desired level of depth.

RTL further outlines a dynamic account of inference where surprise is minimized, with surprise defined as the difference between the beliefs about the process based on knowledge of the larger state space and outcome of a realization of the process on the trace. This is equivalent to many formulations of perception/cognition, such as those coming under the header of "active inference" (Clark, 2017; Parr et al., 2022). However, unlike the standard active inference models, in the case of RTL this minimization of surprise is defined without the assumption of a material substrate, a seemingly rigid internal-external decomposition, or, indeed, any "true" observable world state at all.

It is worth considering how RTL relates to perception. First we note that individual phenomenology always reflects the currently attended state in the current state space X_n as specified by all retracing operations up to the point time step n. This current state space X_n, together with its transition kernel, might be a combination of a number of smaller phenomenological processes, a subset of a larger set of such processes, or just a fine-graining of the dynamics of one particular process. These combinations and adjustments to state spaces are governed by the trace logic, which restricts which types of spaces can be combined, and what expansions and contractions of a state space can look like.

While individual moments of experience are given by the states of X_n, some *long-term* properties of experience rather are reflective of the Markov processes that govern state updates. Thus we expect to be able to show how a number of perceived properties of the physical world emerge out of the structures of these state spaces and kernels. This expectation motivates the formulation of the eight conjectures shown in Table 1 below. Moreover, it adds precision to the "conscious agent thesis" of Hoffman and Prakash (2014), who postulated that "every property of consciousness can be represented by some property of a conscious agent or system of interacting conscious agents."

The trace logic has been developed as a mathematical framework, and has been shown to have properties crucial for modeling networks of interacting phenomenological processes. In particular, it gives the ability to compare such processes and make precise statements about the relationships between them. However, the application of trace logic to *human* phenomenology through RTL is still in its early stages. This is a non-trivial project, since different aspects of reality impose interlocking, and sometimes competing, modeling requirements. For example, recurrent Markov processes, which visit states more

than once, would be useful for modeling certain physical processes, but human subjective experience is usually not viewed as ever repeating in detail. Similarly, reversible Markov processes, which behave the same way backward and forward in time, seem useful for modeling many physical systems that are indifferent to the arrow of time. However, subjective experience tends to flow in one particular temporal direction. Exploring these interacting, and sometimes competing, requirements is expected to guide the modeling work and potentially provide insight into the properties of experience along the way.

The framework naturally aligns with other fields of study in cognition and consciousness research. In addition to the overlap with active inference mentioned above we also note that RTL can be viewed as consistent with the vast field of 4E-cognition (Newen et al., 2018), which argues that embodiment, actions, and phenomenology are intimately intertwined. While ITP and RTL together suggest that embodiment literally emerges along with spacetime as an outcome of structures that are fundamentally phenomenological, there is strong alignment with 4E-cognition in the view that macroscopic material objects are just "data structures" for active manipulation. Indeed, the trace logic might provide a better conceptual framework to accommodate 4E-cognition than a standard materialist reductionist perspective would.

Much of this work can be viewed in the context of conscious realism, which was first articulated several years prior to the initial research on trace logic (Hoffman, 2008), and posits that the entirety of the universe can be modeled as a network of conscious agents. Its primary function is to define a metaphysical framework for understanding the world of a conscious agent, comparable to a "realist idealist" (Chalmers, 2019) perspective. Conscious realism aligns closely with the views of physicists Max Planck and Erwin Schrödinger who both viewed consciousness as fundamental and logically prior to physical matter. RTL provides the mathematical formalism for the development of such a model.

5 The Research Roadmap

We will use recursive trace logic to construct a new science of reality, based on a comprehensive and coherent notion of information that can address both physical matter and human lived experience. While science based on materialist reductionism built the modern world, it is likely to be child's play compared to the type of human civilization that can be constructed based on a holistic scientific theory of reality. The proximal scientific research will focus on connecting RTL to major domains of empirical science to examine whether (1) RTL can generate testable theoretical and experimental predictions that can validate the theory, and (2) the theory can model real-world experimental data, better than models based on materialist reductionism. Due to its revolutionary onto-epistemic implications, we believe this effort is among the most adventurous scientific projects in human history. The following research roadmap outlines several key directions that will be pursued with alacrity.

5.1 Physics: Eight Conjectures of the Trace Logic

By positing a perspective of science based on consciousness, we commit to the task of reformulating physics, replacing its current materialist reductionist foundations. This task is long term, with several intermediate objectives. We describe the overall project, then overview the state of the first part.

We first wish to show that RTL can reproduce central facts of modern physics. Just as Einstein's relativity must agree with Newtonian physics in classical regimes, so RTL

must recover the physics of spacetime. Several approaches are useful in this work. Pure mathematics and computer simulations can generate toy interfaces, exploring the general properties and possibilities of RTL. We then aim to rigorously reconstruct all known laws of spacetime physics, qualitatively and quantitatively. The eight conjectures, listed in Table 1, structure the first steps of this reconstruction. Proving these conjectures is a prime focus of the scientific program.

Table 1: Eight Conjectures. The guide to the regrounding of physics in recursive trace logic.

#	Domain	Conjecture
1	**Special relativity**	Minkowski space emerges as the limiting behavior of Markov chains representing n-cycles as $n \to \infty$ under certain conditions.
2	**General relativity**	Curved spacetime emerges as the limiting behavior of special classes of non-cyclic Markov chains under certain conditions.
3	**Cosmology**	Cosmology and cosmic evolution arise as properties of long samples of certain classes of Markov trace chains.
4	**Planck-scale failure of spacetime**	The breakdown of spacetime at the Planck scale is a consequence of the increase of energy with number of states in a trace.
5	**Quantum wavefunction and Born rule**	Quantum wavefunctions of free particles, and the Born rule, can be recovered from the asymptotic behavior of enhanced Markov chains.
6	**Elementary particles**	Each of the elementary particles in the Standard Model can be identified with a particular class of Markov chains.
7	**Scattering amplitudes**	Scattering amplitudes arise from properties of relevant Markov chains, with ABHY associahedra appearing as subpolytopes of the Markov polytope.
8	**Entanglement**	Disjoint traces of an ergodic Markov chain create spacelike-separated observers with hidden interactions, giving rise to quantum entanglement.

Once these conjectures are proven, we can proceed with the rest of the research program. It will reveal how RTL can derive the experience of physical reality. Recovering known results is essential, but just the beginning. Then we must derive new predictions about a system that operates based on the recursive trace logic. These predictions must be tested by experiments, and the RTL framework revised, based on outcomes.

5.2 Neuroscience: Engineering the Observer Interface

In the materialist reductionist epistemology, the brain is a physical machine, a molecular genetic information processing structure. Consciousness is solely an emergent property of this machine.[6] In support of this epistemology, neuroscience had made progress on the causal mapping of specific brain functions to specific neural circuits. However, this progress is overstated: in domains of higher cognition and conscious perception,

[6]This is underscored by the sheer volume of competing ideas; Robert Lawrence Kuhn recently identified approximately 300 theories of consciousness, the overwhelming majority of which remain tethered to materialism (Kuhn, 2024).

the project of finding the "neural correlates of consciousness" (NCC; Koch et al., 2016), understood as the mapping between neural activity and subjective experience, provides only vague correlations. This has resulted in a field divided into camps that dismiss rival theories as unscientific or unfalsifiable in an endless cycle (IIT-Concerned et al., 2025; Tononi et al., 2025; Gomez-Marin and Seth, 2025). These controversies deflect from the real problem, the failure of neuroscience to solve the "hard problem of consciousness" (Chalmers, 1995), or how and why does physical information processing feel like anything at all?

As with physics, so with neuroscience: a scientific theory that includes the observer and is not restricted only to atomic structure makes it necessary to solve the problem of information processing in the context of subjective experience. According to the trace logic, a physical information processing structure like the brain is an interface representation that provides useful information about properties of subjective experience but not the actual substrate in which experience is produced. In the computer desktop metaphor, the materialist assumption that the brain produces experience is like assuming that an icon on a computer desktop is where computation occurs. Consequently, the hard problem of consciousness is reframed. Rather than asking how experience emerges out of physical systems, we ask how a physical reality emerges out of experience. However, while subjective experience is not neuronal in nature, the physical brain still is an interface representation of experience-dependent information processing. Therefore, our approach to deriving neuroscience from the trace logic is similar to physics. We will "engineer the headset", the observer interface that defines our perceived reality. The trace logic will enable testable quantitative predictions about the NCC, including what kinds of neural states and perturbations may correlate with what kinds of experiences.

Developing a principled understanding of the relationship between the brain and consciousness with the mathematical precision of the trace logic will also be helpful in understanding the biological individual. The trace logic only describes experience in terms of an interlocking network of observers, but it is reasonable to assume that the experience of the self may also involve a higher organization of experiential traces, including the persistence of memory or the integration/segregation of perspectives. For example, RTL may be able to derive individual and shared human experiences as combinations and decompositions of individual experiential processes. Conversely, the trace logic will also illuminate our understanding of *other* individuals, or the possible existence of experiences and their traces external to the brain, including questions about the potential ubiquity of consciousness in nature beyond current physical measurements. This will also allow us to address questions about non-human consciousness ranging from animals to machines and beyond, which is relevant to the future of AI development.

Further advancing a new epistemology for neuroscience in the methodology domain, we will explore a comprehensive phenomenology of human lived experience for the biological self, as discussed above. The massive "dark matter of human experience" has been categorically excluded by the materialist reductionist epistemology. Here, we assume that there are likely to be aspects of consciousness, such as linguistic narratives and experiential point-of-views, which are not ultimately physically situated in spacetime measurements, but are nevertheless amenable to rigorous probabilistic inference for which the Markovian kernel structure of the trace logic seems well suited to engage. From epistemic and ontological perspectives, the unbiased and unconstrained phenomenological stance of the trace logic will in principle enable the inclusion of all observers and observations from physical measurements to accounts of lived experience to build the foundations of a new science of reality.

5.3 Metaphysics: Toward a Mathematical Framework for Spirituality

The trace logic framework is predicated upon the premise of a non-dual mode of existence that transcends the constraints of spacetime, and therefore, is well aligned with diverse contemplative traditions, such as many lineages of Daoism, Buddhism, Vedanta, and others. This reflects not only our mathematical axioms but also a corollary derived from the interface theory: conventional dichotomies, such as "mind versus matter", "real versus imagined", and "internal versus external", fail to accurately characterize the fundamental nature of reality. Instead, these categories are better understood as products of a continuous adaptive process through which we navigate the world. A non-dual perspective provides the only coherent framework for these observations, while a grounding in consciousness makes the model consistent with the reality of our experience. While this might seem a strong ontological commitment, we rather view it as an absence of commitment to the assumption of duality which has been a tacit and limiting assumption of science.

When exploring the properties of experience, it is important to consider the full scope of related observations. Regarding the concept of the self, the role of agency in the evolution of reality, and the relationship between individual consciousness and consciousness at large, there is a large and credible body of knowledge from spiritual and contemplative practice that we view as important input. We expect the trace logic to solve long-standing disagreements and overlaps between these spiritual systems. For example, the trace logic may provide insight on the relationship between the Buddhist concepts of *anatman* (no-self) and the concept from Advaita Vedanta that *ayam atma brahma* (the personal self is the supreme self). Does this distinction point to a substantive soteriological conflict or is it merely a semantic issue? Utilizing RTL we expect to be able to explore these kinds of questions from a novel perspective, with mathematical rigour.

The trace logic also invites inquiry into the concept of free will. The question about the existence of free will currently remains underdetermined in our theoretical framework. For example, viewing probabilities in the trace logic as fundamental, ontic constituents of the theory could lead to two distinct interpretations: (i) they may be understood as the manifestation of free will at the most basic level of the formalism, or (ii) they may indicate a source of principled unpredictability, suggesting an absence of determination by either conscious choice or deterministic natural law. Again, this is a question that many spiritual and contemplative traditions have made statements about, that are worthy of consideration. For example, interpretation (i) resonates with some spiritual and philosophical lineages, such as Christian voluntarist traditions, while (ii) might align better with others, for example, those of some Buddhist schools, such as Madhyamaka (Westerhoff, 2018). Philosophically, this ambiguity is suggestive of an irreducible limitation of human modes of understanding (Kant, 1998). Even if we are unable to resolve this tension, the fact that our framework provides the opportunity for discussing it with mathematical precision is a beneficial development in itself.

5.4 Technology: Innovating a New Science of Reality

Advances in technology tend to accompany major paradigm shifts in science. The Copernican shift, the realization that the Earth revolves around the Sun, not the other way around, took place amid a cascade of inventions, including the telescope, the pendulum clock, and the microscope. Yet the Copernican shift would not have resulted in a genuine scientific revolution (Kuhn, 2012) were it not for new forms of mathematics like the differential calculus of Newton and Leibniz. Likewise, a mathematical model such

as RTL that centers the conscious observer as fundamental to spacetime, rather than the materialist paradigm according to which consciousness emerges from matter, is a reasonable candidate to inspire a comparable revolution in science and technology. If the core tenets of the model can be validated theoretically, along with new empirical evidence from scientific experimentation and data analysis, outlined in the above sections, then a new science of reality with radically different assumptions, rules, and derivations than conventional materialist reductive science will emerge. The fundamental boundaries of science would shift, and the invention of new technologies will fill the open spaces. Here, we outline possible technological domains that may emerge.

Physics and Engineering

Our scientific program may ultimately result in the emergence of new forms of physical engineering. An ability to demonstrate the derivation of conventional physics will be a useful start, but this also opens the door to the innovation of a new area of "generative physics", leading to the search for novel physical phenomena predicted by the trace logic. One candidate for such phenomena is dark matter, and the problem of whether it may be connected to trace networks. Moreover, recent advances by Nima Arkani-Hamed's group in geometric physics also point to a potential integration of surfaceology (Arkani-Hamed et al., 2025) and the functional architecture of RTL, with technologies based on the geometry of phenomenological networks and their predicted spacetime correlates. Finally, ambitious projects could leverage the freedom from the constraints of the spacetime headset to manipulate the properties of spacetime itself.

Human Intelligence

One application of RTL is to reverse engineer the interfaces between conscious observers. This may also open up the possibility of new technologies that can allow scientists and explorers to build new interfaces, both in conventional spacetime and beyond. For example, DMT is a pharmacological tool to explore new realms of experience, and work has already begun on applying our framework to DMT experiences (Gallimore et al., 2026). However, this methodology is not limited to pharmacological interventions, but it also extends to contemplative practices, psychopathology, and technological methods such as direct brain stimulation by ultrasound or microwaves (Pereira et al., 2024; Lord et al., 2024). In addition, this work has the potential to contribute to the field of neurophenomenology (Varela et al., 2017). As such, RTL will offer tools for consciousness science that may enable new ways to modulate the state of the brain to study, model, and manipulate human consciousness. The goal is to bring experience into the purview of engineering, since a mathematically precise model of experience will provide the same type of leverage over our mental world as the development of physics provided over the physical regime. It is hard to overstate the transformative effect that this will have on fields as diverse as psychology, medicine, spiritual practice, social science and economics.

Machine Intelligence

RTL provides a radically different and more fundamental perspective on the development of artificial intelligence (AI). Because the trace logic places consciousness at the base of reality, any derivative computational architecture will reflect this novel "microchip epistemology". For example, conventional architectures of deep learning networks are highly inefficient and energy consuming compared to the human brain. However, it

has proven to be difficult to leverage this biological efficiency when designing artificial systems. This is not surprising given our view that the brain must be understood as an interface representation, not as part of physical "ground reality." In contrast, RTL may allow a wider aperture for the design of computational architectures. The hidden network of experiences can be regarded as a distributed, non-spatiotemporally constrained computational reservoir (Gauthier et al., 2021) with tunable read-outs to assert functional dynamics and leverage highly efficient small-world topologies. Such networks could herald a computational paradigm as transformative as today's attentional architectures (Vaswani et al., 2017), yet functioning beyond the conventional boundaries of spacetime.

Abbreviations

The following abbreviations are used in this paper:

ITP	The Interface Theory of Perception
NCC	Neural Correlates of Consciousness
RTL	Recursive Trace Logic

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