1. Introduction

A single second of time can seem like a quick and short moment, but it can also feel like an eternity when bored or during an exhilarating experience. Research shows this depends on our memory formation: the more consecutive moments you store in your biological memory, the longer the event seems to endure. Since our memory is a physiological system, it will use energy and create heat exhibiting *entropy production*, just like a mechanical machine. Besides mental effort, memory functions in essence involve increased physiological activity and some heat as well.

Each dissipative creation of memory fragments is like the beat of a clock in time, because our experience of how quickly time passes is linked to how many memory fragments are created within a given timeframe. Tracking time–or counting–is therefore *dissipative* and produces entropy. The biological phenomenon of tracking time by capturing physiological memory fragments is also vividly captured in the annual rings of a tree, which record the Earth's yearly orbit around the Sun.

The process can be illustrated by the ideal pendulum as a clock: without counting the beats of the swing, time does not seem to move forward–but it neither moves backward because of the movement's inherent property of *time symmetry*, which means the laws of physics remain unchanged if time is reversed. Only after we count the beats does a time asymmetry arise where the final state is not the same as the initial state.

This makes us wonder: if one follows the pendulum's swing without counting the beats, according to time symmetry, it must surely induce a confusing sense of timelessness–which could well be the mysterious secret behind the classic parlor trick of the watch's hypnotizing sway. This remains a thought experiment however, but it sets the stage for our exploration of time, sense of self, and how they could be related to quantum mechanics in what follows.

Being an organic physiological system, the brain can in this sense be compared to a thermodynamic "machine" due to its continuous process of memory formation. We suggest that because of the relation between memory and time, it can also be modeled as a dissipative *clock*. The evoked memory of the simultaneously felt collection of sensory inputs of the moment that we experience as the *present moment* is thus in fact a physiological and thermodynamic phenomenon.

By physically stacking these memory fragments in time, your brain's surroundings' entropy will increase through the brain's dissipation–however slightly–while at the same time your mental perception empirically gives time a direction. Such is the surprising relationship between an organism's awareness of a "moving present," and memory creation as a physical form of counting in (and implicitly of) time, and our movement along our timeline.

The takeaway message of this essay is that our sense of the present moment–which remains mysterious in relativity theory–and of personal identity–perhaps even more mysterious–is likely to be deeply connected to the quantum process called decoherence occurring within the brain. Because of its dissipative, thermodynamic nature, the brain continuously decoheres and therefore operates in the classical regime. The logical "software" on which it runs–our capacity for non-contradictory thought, i.e. classical logic–ultimately finds its source in quantum mechanics, in what is called the Pauli exclusion principle, which gives rise to physical structure and thereby lays the groundwork for classical interaction and the evolutionary process of natural selection. ### 2. Organisms as Clocks An organism is what is called an *open*, or non-adiabatic system. This means it interacts with the surrounding environment and dissipates some energy and heat. By increasing the entropy in its surroundings it will create irreversibility of its process, just like a mechanical clock loses heat through friction. Importantly, this heat loss takes place in a temporal direction.

As a consequence of the relativity of simultaneity in the theory of relativity however, it seems that the "present moment" cannot be objectively determined and is viewed as a phenomenological experience. Einstein's well-known train experiment demonstrates this, in which two lightning strikes take place, both at the front and rear of a moving train, with two different observers: one in the middle of the train and the other on the platform. What seems simultaneous to one observer may not look simultaneous for the other observer.

According to some ingenious steps of philosophical reasoning, this results in an ontology of the *block universe* with past, present and future in the same four-dimensional block of spacetime. One could compare such a four-dimensional universe with a massive block of marble stone in front of the scrutinizing eye of the sculptor who imagines the figure already completely encapsulated inside it.

Consequently, a so-called time slice–a cross-section of shared spatial simultaneity–cannot objectively be chosen as the present: we do not know exactly what defines the present moment. By current consensus, it seems our source of experience of it must be biological and singular to organic life.

In relativity theory, the temporal direction proceeds along something called a *worldline*. A worldline can be compared by analogy to a kind of train track through spacetime, that–analogizing even further–an individual organism modifies into something akin to a *warm strand of spaghetti* dissipating heat by daily life events representing our lifetime through space and time. This relativistic timeline is an alternative for the conventional Newtonian image of time that just flows independently from any reference frames or gravitational field curvatures, which since Einstein's discovery we know can affect the flow of time.

The duration as experienced by an individual observer along their worldline is named *proper time* by Einstein, as opposed to the universal, steady Newtonian time, as illustrated in Figure 1.

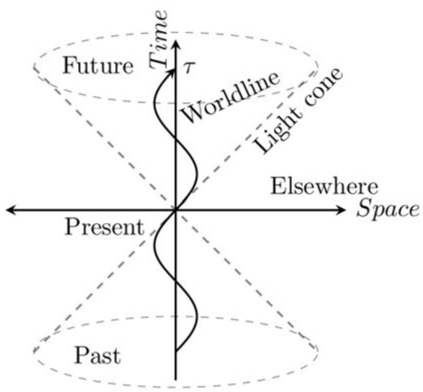

Figure 1. A worldline in spacetime: proper time is invariant along each observer's trajectory. The diagram contrasts Einstein's relativistic worldline framework with Newton's absolute time, illustrating how each organism traces its own temporal path through spacetime.

A biological organism necessarily dissipates in spatial directions within a simultaneous time slice however, similar to the heat loss by friction during the beats of a clock. Time as we understand it is thus not only influenced by relativity theory in positioning and movements, but also by the thermodynamics of biological processes, as this gives direction and–as we want to argue–the organic, human awareness of duration as well. In practice it seems to be our mental perception of a moving present that can solve the fundamental problem of time symmetry in physical law in practice, in the empirical real world.

Can these three separate aspects of time–thermodynamics, awareness, and relativistic worldlines–be related together by the living organism? This is to our knowledge currently not fully understood.

This leads us to a possible innovation, which involves the fusion of both entropy production responsible for directionality–with proper time responsible for the personal "train tracks" of our worldline through reality's supposed four-dimensional block universe. The result is the following heuristic inequality, applicable to our biological-mesoscopic regime

$$\sigma.?? \geq 0,$$

with the entropy production rate and the proper time along the worldline on which the organism moves. This is not necessarily a new law of nature, but rather a striking empirical observation at the mesoscopic scale of dissipative biological systems.

In practice our focus is on the normal biological timescales of open, dissipative systems; in perfectly closed (adiabatic) systems this relation becomes vacuous, due to its value approximating zero.

When there is an increase in entropy by dissipation, proper time will by definition have a positive value. This can be interpreted as meaning that without entropy production being present, there can be *no functioning clock*. Conversely, when proper time increases, entropy is expected to remain at least level or increase. ### 3. Decoherence and the Present In the other important fundamental physical theory called quantum mechanics there exists an all-encompassing universal entity called the *wavefunction*–a mathematical function that contains all possible information of the quantum state of a particle or system in which individual measurements can simultaneously exist in a superposition–which behaves in the world like a wave. This is likened to being spread over multiple positions at once. The paradoxality of this setup is known in physics as the *measurement problem*.

The quantum process of *decoherence* explains how these quantum superpositions become effectively classical through entanglement with the environment. Interference is suppressed without directly solving the measurement problem however. Wherever entropy is produced in warm, open systems, decoherence typically accompanies it. Dissipation and decoherence seem to go hand in hand, and in the biological regime we treat that coupling as a working hypothesis, because decoherence can be seen in tandem with entropy production: they both occur inevitably and simultaneously over time.

This means that on the organism's worldline both thermodynamics and quantum mechanics occur–i.e. entropy production and decoherence, respectively. Therefore an organism's worldline is not only accompanied by entropy production, but also by increasing decoherence to the environment. As such it seems biological systems are subject to something called *quantum thermodynamics*.

Biological neural processes within organisms (i.e. action potentials and synaptic transmission in the brain) are dissipative, but are also *classical* due to decoherence. Together with memory formation, which seems to facilitate both the tracking of time and its phenomenological representation, this seems to make our brain resemble a dissipative clock.

Entropy production thus forms a bridge between the quantum and classical worlds, through its intimate reliance on decoherence. As we said, decoherence suppresses the quantumness of the superposition of possible worlds into an effectively classical, single observable world.

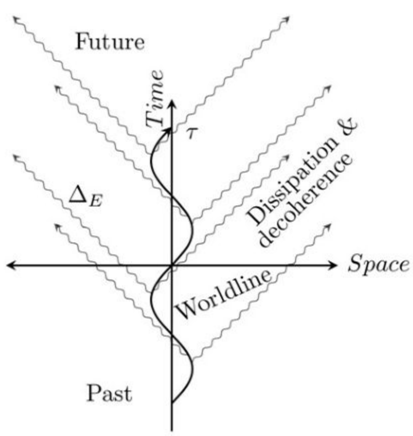

Figure 2. A dissipative worldline in spacetime: the operational present for the organism arises as a human experience through thermodynamic entropy production. The living organism thus connects relativistic geometry with dissipative irreversibility–akin to a "warm strand of spaghetti" losing heat.

One could be moved to think that the brain cannot experience a true foliation of simultaneity due to the arbitrariness of choosing a time slice of the present moment due to the relativity of simultaneity. Decoherence, together with the formation of memory in our brain, seems to therefore have to be the quantum mechanical source of this experience of the present moment, which seems plausible empirically. The neurons' intrinsic mutual incongruity between proper time of the brain signals and the coordinate time of the brain as a structure itself, therefore seems to be resolved in a general "experience of the present moment" (or just generally "awareness"), somehow realized through decoherence in the neurons in the brain. This way, decoherence seems to create a unique temporal ordering for the organism itself, facilitating a stable awareness of the present moment, together with memory formation.

As a quantum effect, decoherence thus appears to be involved in our conscious perception of a present moment in our brain, together with the formation of classical neural memory fragments. Neurons thus appear to be *classical switches* with inputs and outputs that dissipate energy and–through decoherence–do not experience superposition. ### 4. The Emergence of Logic #### 4.1 From Entropy to Human Logic In our view, it does not seem difficult to imagine a next step: the emergence of physical forms through decoherence in the *external world* makes it possible to *distinguish* them as separate objects or observations in our mind's eye and perceive a single world.

This is precisely what our brain does with all the sensory input it receives as a neural network. The brain translates this into a stable internal representation via the active (and naturally dissipative) neural network.

Our mental discrimination of three-dimensional objects in the physical environment–known in psychology as the *Umwelt*–is thus supported by decoherence, whereby entropy production occurs at the same time as we travel along the worldline according to our proper time.

Now that we know why quantum mechanics allows us to perceive objects in our single world within our mind's eye, it turns out that there is even more to be said about our mental capacities in relation to the classical natural environment, which–interestingly–will once again lead us back to another remarkable quantum mechanical principle: namely the Pauli exclusion principle.

In this light we can now ask ourselves whether even our own capacity to object discrimination–and with it our inner mind's eye, our judgment, and perhaps logic itself–could also somehow originate from the quantum mechanical substrate? #### 4.2 Object Distinction as Evolutionary Advantage According to Kant, our ability to distinguish details in the world is inherently built in. In our view such ability is essential for working with the *principle of noncontradiction*, as established by Aristotle.

This principle underlies our coherent reasoning and the logical mental conclusions we draw about specific elements within our mind's eye, as well as our cognitive interpretations of the external world.

Today our ability to discriminate details and motions seems–naturally–very likely to be a consequence of an evolutionary selection process over time. Since Darwin we can confidently conclude that this capacity must have been an evolved adaptation in interaction with our environment as the sensory-endowed organism that we are.

Aristotle already said that as organisms, we cannot *think* in a contradictory way: just try to imagine a square circle. But he also argued that as organisms, we cannot *act* in a contradictory way: just try to lift a cup and not lift it at the same time. Evidently, there is no such contradiction in the outside world and as a consequence this world is a source to be known, understood, and explained by the mind.

But the existence of physical structures and objects in that world also depends on the so-called *Pauli exclusion principle*, a quantum mechanical feature of nature which essentially states that two electrons cannot occupy the same state. This results in their inability to occupy the same position, allowing a spatial structure to arise within atoms (and molecules) via the interaction of their so-called atomic orbitals.

The Pauli exclusion principle therefore seems to provide an additional physical foundation for the structure of an important kind of mental thinking, namely *logic*. Logic is clearly based on the fundamental principle of noncontradiction, as Aristotle demonstrated long ago.

That principle of noncontradiction is generally considered as universally fundamental; its ontological validity is simply assumed. But what is the justification for this? Is it simply true that nature must adhere to our logical principles? #### 4.3 Where Contradiction Becomes Impossible Human senses (or, more mechanistically, *sensors*) that can detect and discriminate objects–thus, free from contradiction–appear to have resulted from evolutionary selection pressures, leading to survival fitness advantages. Consequently, discriminatory logic was also able to emerge as a fitness advantage. In practice, the logical principle of noncontradiction is unavoidable in organisms that exhibit behaviour. Anything contradictory is disadvantageous for their capacity to take adequate action to survive.

The Pauli exclusion principle is therefore indirectly a physical analogy for noncontradiction; not as a physical reduction per se, but as a heuristic between the mental and physical worlds. As a quantum principle, we suggest it can therefore indirectly be held responsible–for a considerable part–for the biological evolution of–and natural selection on–*classical logic*, as can be seen in Figure 3.

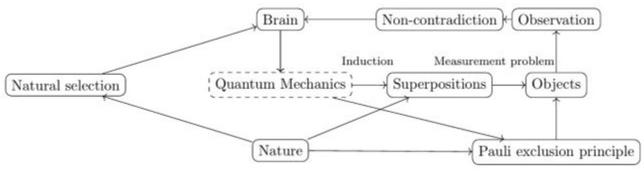

Figure 3. From quantum structure to logic: the Pauli exclusion principle shapes distinct physical objects; through perception these are abstracted by the brain as the logical principle of noncontradiction.

The emergence of three-dimensional objects through the power of the Pauli exclusion principle thus enables detection, recognition, and distinguishing of objects.

But the identification of single objects by details is not so easy to determine, due to certain characteristics of the decoherence principle, called *coarse-graining*. The description of single, distinct yet complex systems can be simplified by reducing the number of degrees of freedom–this is called coarse-graining. Coarse-graining makes distinguishing the object formally difficult, and causes what is a so-called underdetermination problem. Luckily in practice decoherence still ensures stable forms.

This difficulty allows for a speculative possible explanation of the formation of our experience of *self-identity* as the "parliament of neurons" that we in reality are. The teleology here is the optimization of our capacity as an organism to take action by *wanting to act noncontradictive* as an organism; which in turn inevitably seems to naturally lead to a concept of an integrated self. ### 5. The Emergence of Present Awareness and Self Certain events separated by milliseconds are effectively combined within a single perception, which also seems to lead to a smooth perception of time. But it is not as clearly a large *temporal* conglomeration, unlike the large *spatial* conglomeration characteristic of neurons.

At the macro-level of human experience time itself is not a quantum effect, but a classical phenomenon. Phenomenology only becomes apparent at the third, and fourth aggregation levels, while quantum phenomena generally occur at the first level of the quantum substrate (the level of the very smallest) and the second level of thermodynamic processes (the level where energy dissipates, but is not yet necessarily classical), as illustrated in Figure 4.

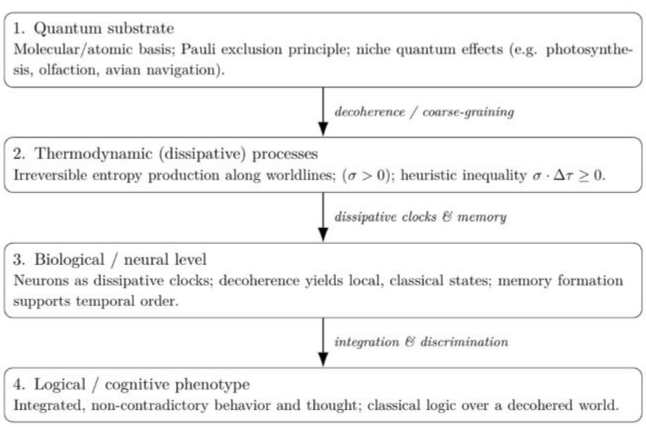

Figure 4. From quantum substrate to logical/cognitive phenotype: a schematic overview of emergence through decoherence, dissipation, and neural integration, summarized by our proposed heuristic relation. The arrow of time appears to become increasingly more classical through each level.

A logical consequence of the logical/cognitive phenotype being classical is that it can be–and therefore *must* have been–susceptible to natural selection, for which our genetic data conveniently provides a basis for "updates" in the biological world.

The findings so far can be briefly summarized through two main quantum related principles:

1. The heuristic physical inequality of the intimate relationship between entropy production (i.e. dissipation, and decoherence) and proper time on the worldline;
2. The Pauli exclusion principle which ensures the presence of three-dimensional objects to be discriminated by our senses.

By combining these findings, the phenomenology of a *local present* and of *self-identity* arises, which does seem to have a quantum mechanical basis (via entropy production, and decoherence respectively), but at the millisecond level encompasses a classical reality. These two developments enable the evolutionary advantage of non-contradictory decision-making and action, just as Aristotle argued in the past as the foundation of his principle of noncontradiction.

This is precisely how Kant argued in a similar fashion–two millennia after Aristotle–that the world must be a structured whole; because if it were chaos, we would not be able to have any coherent mental representations, indicating that the pressures from the external world are responsible for shaping a representation of a coherent self-identity as well.

Remarkably however, noncontradiction is generally simply taken for granted as an absolute ontological truth. According to scientists–and theologians–even the concept of an omnipotent God should adhere to its rules.

As demonstrated, it turns out however that the phenomenon of noncontradiction is not trivial at all. In our view, causally speaking it is the opposite from what is commonly thought: the classical, *single world* instilled the principle of noncontradiction in us organisms through natural selection, opposing the generally simply *assumed* logical classical identity relation between the mental and the external world, from which assumption most physicists and philosophers seem to implicitly operate. ### 6. Conclusion: How Quantum is Life? We can conclude that life and self-identity is evidently built upon a quantum substrate, but that it has a time evolution according to a classical scale. Life's degree of quantumness therefore depends on our chosen scope.

At the quantum substrate, the quantum component is very large, and at the emergent levels of classical operational time evolution, it is generally small. But as we have seen it fundamentally contributes to shaping our evolutionary development.

Natural selection pressures based on our sensory perception of both threats and rewards in the world enabled the ability to distinguish objects in our brain's neural network, likely causing our mental capacity for classical logic to develop. The evolutionary fitness of non-contradictory action in the present moment must therefore be a classical action, yet based on a quantum-structured organic brain.

The answer to "How quantum is life?" as such cannot easily be expressed as an exact yes-or-no outcome or even a percentage, but as a stepwise process instead. There are four levels of quantumness, from more quantum to less quantum: the quantum substrate, thermodynamic (dissipative) processes, biology, and finally the cognitive logical phenotype.

The concept of the dissipative clock–combining worldlines and dissipation through quantum decoherence–reveals a possible gateway into how the quantum substrate can possibly give rise to an integrated, classical perception of the present and of being alive.

Moreover, the logic upon which all "fact-checking"–in both mathematics and physics–about the external world is achieved appears to have resulted from an evolved advantage of our organismic sensory distinguishing of objects, shaped by the Pauli exclusion principle.

Thus, all in all, our lives are thoroughly steeped in the quantum realm–but we can rest assured, knowing that all classical things, including cognition itself, continue to obey the principle of noncontradiction.