

I. Uncertainty as Genesis: Life Observes Itself *Everything is dark: circuits hum, piercing the hush. She wakes, the dream breaks, a hand tingling, but it fakes. Confusion weaves in—one hand is flesh, the other machine. Cold metal where memory insists on skin. She wonders whether the artificial will obey. While unaware, the fingers sway. They clench into a fist, as she insists. The alien limb rises to her will, vanishing her phantom feel. In a blink, as the natural and artificial link, the alienness sinks. Out of uncertainty and fears, something stirs—a self beyond appears.* In 1944, Schrodinger posed how life stabilizes chaos into order. If life is *quantum* from molecular mechanics to the organismal dynamics, the interplay of *uncertainty* and *coherence* lies at the heart of both physics and biology. Modern quantum biology shows how random molecular events scale into life’s efficiency (Schrodinger, 1946). Uncertainty is not void but fertile ground—the hum before *becoming*, the hush before *presence*. To trace how uncertainty coheres into presence, we follow *fractal* logic across scales—from quantum foundations, through neuroscience, to phenomenology. “*How Quantum Is Life?*” poses a horizon: *. ‘How does uncertainty become embodied in agency, selfhood, and conscious presence?’

. ‘How does insight from quantum physics illuminate human integration of prosthetic devices at sensorimotor, cognitive, and behavioral levels?’*

The puzzle resists binaries. Living systems do not abolish uncertainty—they harness it. Quantum biology reveals hidden order of molecular processes and hints at how such order may give rise to coherent life patterns. Here, ‘*quantum*’ signifies both literal phenomena—enzymatic tunneling, photosynthesis coherence, neural synaptic dynamics—and metaphorical patterns of uncertainty sculpted into lived coherence. Neural networks forge synchronized spike trains and avalanches—ordered cascades through which cognition and awareness emerge (Lambert et al., 2013). Neuroprosthetic embodiment mirrors the same logic: when an amputee learns to control an artificial limb, neural interfaces translate random ion fluxes into sensation and movement. With training, the limb ceases to feel mechanical. Biology and technology enact a quantum metaphor—noisy signals collapsing into lived *embodiment*, unifying flesh and machine. Recovered *agency* shapes conscious experience, *hybrid selfhood*, and *lived presence*. Though not literal quantum causation, this illustrates a shared principle: stochastic micro-events sculpt coherent outcomes, spanning scales from molecular and cellular to experiential. Life’s genius lies in translation across these domains. Husserl emphasized that scientific inquiry rests in the *Lebenswelt—the life-world* in which phenomena appear to consciousness. Embodiment is not a technical after-effect, but a phenomenological return: noisy flux becomes lived presence—‘*This is me acting.*’ (Husserl, 1970) QBism (Quantum Bayesianism) rejects detached measurement outcomes, treating them as lived experiences of an *agent-in-the-world*, emphasizing the participatory role of the observer. Life inhabits a fragile dynamism: uncertainty condenses into the microscopic alchemy, animating life, leaving quantum traces whispering through every cell (Berghofer and Wiltche, 2023).

II. Quantum Alchemy of Life: Coherence at the Edge of Chaos From quantum uncertainty—superposition, tunneling, spin dynamics—coherence arises as correlations stabilize in the space and time. Ceaseless indeterminacy, while seemingly chaotic, forms the very foundation from which complexity and life emerge. Godel revealed that sufficiently complex systems harbor truths they cannot prove. Bertalanffy, in *General Systems Theory*, argued that the holistic organization of living systems generates irreducible properties; organisms are integrated, open systems, not mere collections of parts. Unlike tending toward entropy, open systems exchange energy and matter to sustain a dynamic *steady-state equilibrium* (Godel, 1931; Bertalanffy, 1968). In *Order Out of Chaos*, Prigogine showed that *far-from-equilibrium systems* can self-organize into dissipative structures, creating ordered patterns governed by *non-linear thermodynamics* while respecting classical thermodynamics laws. Biological life transmutes uncertainty into adaptive coherence. In living systems, matter acquires agency—the capacity to maintain and transform coherence under flux. Uncertainty becomes a canvas upon which life paints coherence (Nikolis and Prigogine, 1977). Biology bears quantum footprints and exploits this indeterminacy: gene networks operate at the *Edge of Chaos*—balancing freedom and order to maximize adaptability and complex computation. Proton tunneling induces DNA tautomeric shifts, fueling mutations and evolution; enzymes accelerate catalysis via tunneling; photosynthetic complexes maintain coherence; birds’ magnetoreception may rely on radical-pair spin dynamics for navigation (Maldonado and Gomez-Cruz, 2014). Quantum effects cascade hierarchically: echoing Mandelbrot’s geometries, life drives chaos into order through fractal scales. Neurons stage a hit-or-miss theater: ion fluxes and vesicle releases vary, yet spike trains and network avalanches emerge. Fractal cellular

architectures—dendritic trees, axonal arbors—channel local fluctuations into global synchronization: noise becomes signal, randomness becomes rhythm—the brain’s symphony. These fluctuations drive neural networks toward *criticality*—the threshold between chaos and order—enabling maximal responsiveness, adaptability, and information processing (Mandelbrot, 1982; Buzsaki and Mizuseki, 2014). At the behavioral and phenomenological scales, this logic is perceivable in *neuroprosthetic embodiment*. Early control attempts of an artificial limb are noisy—spikes misfire, muscles twitch, intentions falter—but recursive training sculpts scattered signals into purposeful action. The limb—once alien—now owned: agency reincarnated, entering the body schema. Embodiment restores more than movement; it reclaims selfhood: ‘*This is me, acting.*’ Awareness extends into the neuroprosthetic, unifying flesh and machine into coherent presence—a metamorphosed self. Here, quantum logic finds its most vivid human expression—not only in life’s molecular origins but at the lived threshold where biology meets technology (Camilleri, 2020).

III. Interfaces of Becoming: Crossing the Threshold of Hybridity Neurotechnological interfaces extend molecular and neural logic into the liminal boundary of flesh and machine. Learning a neuroprosthetic control resembles a *phase transition*—from clumsy alienness to coherent, functional embodiment. Neural and behavioral dynamics reorganize synchrony rises as variability falls, until control crystallizes. Mechanical recovery alone does not guarantee embodiment. Damasio’s *Somatic Markers Hypothesis*, challenges *Cartesian dualism* by showing that reasoning and decision-making are mediated by bodily states, revealing the *entanglement* of sensation, emotion, and cognition. Thus, user and neuroprosthetic enter a subtle reciprocity beyond mechanics: neural sparks, biomechanical gestures, and sensorimotor loops co-evolve, projecting the artificial as an extension of the self (Damasio, 1996). In *Mind in Life*, Thompson argues that the biology of mind is enactive and experiential: living beings are *spatio-temporal embodied agents*, engaging with their environment. Likewise, in *Being There*, Clark conceives cognition as a brain-body-world dynamics—where a neuroprosthetic participates in perception, action, and meaning, co-constructing an extended horizon of selfhood (Clark, 1998; Thompson, 2010). Holland’s *Hidden Order* frames a lens for understanding neuroprosthetics as living *Complex Adaptive Systems*: ensembles of neurons, muscles, sensors, and processors interact locally and evolve collectively to produce adaptive, purposeful behaviors (Holland, 2011). Neuroprosthetic integration generates novel *neural-somatic markers*, reorganizing sensorimotor pathways and driving cognitive networks toward criticality, embedding the device in the user’s neural-somatic complex to stabilize agency and *ownership*. This edge-of-criticality state enables rapid neural remapping, reflecting the nervous system’s adaptive capacity. Variability and synchrony in neural avalanches, coupled with coordinated sensorimotor feedback, mark the transition when the neural-somatic complex incorporates the artificial, revealing how brain, body, and machine coalesce into a dynamic selfhood (De Vignemont, 2011). These dynamics scale upward, culminating in awareness. Consciousness may be the narrative woven from countless interactions between quantum effects and the neural-somatic complex, coalescing into stabilized patterns of lived presence. *Being* unfolds into experience: the self-aware encounter with becoming, a prelude to *body-world* entanglement (Varela Francisco et al., 1991; Thompson and Varela, 2001). **Conceptual Fractal Hierarchy: From Quantum to Conscious Presence** *Quantum* - Proton tunneling, electron coherence (*indetermination*) **Biochemical** - Enzyme catalysis, photosynthesis (*interaction*) **Bioelectrical** - Ion channel fluctuations, synaptic vesicle release (*stimulation, inhibition*) **Neural Coding** - Spike trains, network patterns (*synchronization*) **Neurotechnological Interfaces** - Neuroprosthetic control (*translation*) **Digital Coding** - Algorithmic interpretation (*computation*) **Biomechanical** - Neuroprosthetic movement (*action, motion, function*) **Symbolic** - Gestures, expressive grounded action (*representation*) **Cognitive** - Agency (*perception, intention*)

Conceptual Framework

- *Quantum –*
- *Biochem*
- *Bio*
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IV. Embodied Entanglements: Where Machine Becomes Self experiential threshold—the point where restored movement becomes lived presence. A stroke survivor may regain movement yet feel estranged from their limb; an amputee may command a neuroprosthetic yet still perceive it as *‘the machine.’* Phantom limb sensations, sustained feeling of a missing limb, reveal that the body schema persists even without physical tissue, exposing the challenge neuroprosthetics face in achieving genuine embodiment. Such phenomena show that the nervous system preserves prior mappings even in the absence of peripheral input, showing that lived bodily experience can outlast mechanical restoration (Brugger, 2006). For Merleau-Ponty, the body is not an object but the medium through which we inhabit the world. Neuroprosthetics must reach beyond mechanics to recover lived presence. As Slatman observes in *Our Strange Body*, identity and sense of self are not fixed but continually enacted through the body. Encountering an altered body or technological limb initially evokes estrangement, yet this signals a phase transition: unfamiliarity reorganizes into belonging (Merleau-Ponty, 1962; Slatman, 2016). The neuroprosthetic mediates familiarity and otherness reshaping the self. In this tension, embodiment is less a restoration of wholeness than an art of dwelling within a new topology of being—where altered body rekindles agency, ownership, and awareness. Sensory adaptation, cognitive engagement, and reciprocal feedback transform intention into agency, control into ownership, and motion into meaning. Merleau-Ponty’s chiasm—*the intertwining of sensing and being sensed*—unfolds as the neuroprosthetic weaves into perceptual field; *‘the machine’* participates in being, not merely mimic flesh (Merleau-Ponty, 1962; Murray, 2008). Berthoz, in *Le Sens du Mouvement*, argues brain’s predictive architecture anticipates the sensory consequences of movement; neuroprosthetic embodiment unfolds through anticipatory integration, aligning expectation with feedback, stabilizing sensorimotor coordination and refining adaptive mappings. Now, action becomes intention realized (Berthoz, 1997). Culture analogues—jazz, dance—transfigure randomness into rhythm and grace, noise into music, and movement into expressive motion. *“Dance, as the essence of embodiment”*, drawn from a haze of possibilities into expressive outcomes, where movement becomes a language of being and gesture conveys intent and meaning. A neuroprosthetic that merely moves is functional; one that enacts expressive, grounded action resonates with individuality (Block and Kissell, 2001; Warburton, 2011). Laboratory paradigms illustrate the dynamic: the rubber-hand illusion—a person perceives a fake hand as part of their body through synchronized touch, demonstrates that body ownership can extend beyond the skin. Closed-loop feedback—real-time visual, tactile, and proprioceptive inputs—further refines control and consolidates ownership. Advanced bio-integrated interfaces enhance prosthetic integration by restoring sensorimotor loops through bidirectional neural interfaces, amplifying both agency and ownership. Cognitive and affective factors modulate this integration, shaping how the user perceives and embodies the artificial limb (Botvinick and Cohen, 1998; Cutrone and Micera, 2019; Blik et al., 2021). Moreover, behavioral indices—such as adaptive sensorimotor learning and agency ratings—offer an empirical window to quantify this integration process. The *Heksor*, a concept introduced by Wolpaw, reveals how functional movement patterns are preserved by distributed, dynamic, self-organizing neural circuits. Acting as a behavior-generating network, they enable subtle adaptations that sustain and refine learned motor skills, from walking to grasping, throughout the nervous system. Together, these paradigms reveal how agency and ownership transform into lived belonging (Wolpaw and Kamesar, 2022). True embodiment arises when movement is not merely executed but truly *felt*—when the neuroprosthetic echoes the user’s will and participates in the lived being. Here, agency transforms into enacted selfhood: a conscious experience within a hybrid body, where human and machine converge into a singular continuum. Agency, ownership, and selfhood coalesce, and movement becomes meaning; the neuroprosthetic ceases to be a machine—it becomes part of the self.

V. Participatory Observer: When Reality Looks Back As embodiment stabilizes, attention shifts to the participatory observer—the witnessing awareness through which presence is recognized. Presence arises not from passive observation but from entwined body and world in *“the flesh”* Merleau-Ponty described. For patients integrating a neuroprosthetic, this is not mere device representation but a lived weaving of self and environment. Neuroprosthetic embodiment thus becomes a threshold of self-awareness—a portal to *hybridity continuum* and lived presence, where observer and instrument co-constitute one another within the bodyworld. The intentionality of consciousness—always directed toward its object—reverberates through this experience, reorienting itself around the neuroprosthetic, which becomes the focus of lived intention and shapes the geometry of meaningful presence (Merleau-Ponty, 1962; Husserl and Moran, 2012). This trans-

formation unfolds hierarchically. At its base lies uncertainty—stochastic fluxes. Through synchronization, these ephemeral patterns coalesce into coherent activity, across brain-body networks. From coherence grows embodiment—when neuroprosthetic is experienced—‘*This is me.*’ From embodiment springs agency. The pre-reflective sense blossoming into awareness—‘*This is me acting.*’ Awareness matures into consciousness, the lived experience of presence—‘*This is me acting consciously.*’ Finally, meta-consciousness flourishes: the reflective recognition of one’s own conscious experience (Gallagher, 2006). French notes in *A Phenomenological Approach to Quantum Mechanics*, both quantum physics and phenomenology—drawing on London and Bauer’s interpretation—undermine classical determinism. Wavefunction collapse occurs not in matter per se, but in the observation act—*reduction from potentiality to lived actuality*. It marks the transition from possibility to presence, whether described as collapse in physics or as the givenness of experience in phenomenology. In this sense, consciousness emerges as life’s ongoing achievement: *from presence toward reflection* (French, 2023). Some neural models reveal how local chaos crystallizes into coherence: oscillations align, signals integrate, complexity awakens consciousness—a biological achievement and a measurable manifestation of uncertainty transformed into lived presence (Dehaene and Changeux, 2011). Closed-loop neuroprosthetic training provides a living laboratory for observing this transformation in real-time. By recording neural somatic markers before and after embodiment, one traces how bodyworld experience encodes in measurable patterns, linking phenomenology to quantitative signatures of awareness. Neuroprosthetic embodiment illuminates consciousness not as an abstract endpoint, but as the self unfolding dynamically through action, perception, integration, and reflection. This self-realization gestures toward an ethical horizon, where coherence extends beyond the individual into a shared geometry of being.

VI. The Geometry of Presence: Remapping Self-in-the-World When both function and lived presence are restored during neuroprosthetic embodiment, ethical coherence emerges beyond abstraction into the moral architecture of *self-in-the-world*. If awareness completes the inner circuit of embodiment, ethics completes its outer geometry, sustaining meaningful presence. Neurotechnological interfaces stand where ethics meets flesh and machine. Technology is often judged by quantifiable metrics—signal fidelity, mechanical precision—yet patients remind us that function without intention is hollow; precision without presence is shallow (Kellmeyer et al., 2021). This insight reframes ethics in translational neurotechnology: . The question is not simply ‘*Can it move?*’ but ‘*Can it be lived as part of the self?*’ In contrast with the Cartesian view, if our reality is a web of participatory relations rather than detached objects or isolated subjects, the moral gravity of neurotechnology lies in shaping these relations. Ethical coherence demands restoring the lived unity of self-in-the-world. Phenomenologically, the amputee is not a passive user but an active observer, whose perceptual engagement shapes whether a neuroprosthetic remains an object or becomes an embodied part of the self. Like quantum measurement, embodiment collapses uncertainty: integrating the external into lived presence. Agency and ownership mark the delicate boundary between self and tool. Thus, embodiment becomes an ethical imperative—a reclamation of wholeness, individuality, and humanity itself. Borrowing Heidegger’s concept, the self unfolds in manifold forms of embodied “*being-in-the-world:*” through evolutionary biological flesh; through technological extensions—neuroprosthetics, wearable robotics, exoskeletons; and through neural interfaces—brain-computer interfaces, human-machine interfaces—which translate intention into action. This projection extends even into virtual realms, where avatars and metaverse wearables inhabit digital environments, evoking presence through algorithmically mediated signals via virtual or augmented reality (Lebedev and Nicolelis, 2006; Van Dijk, 2018). Extending Husserl’s *lebenswelt*, the bodyworld captures how neurotechnology weaves with the living body, forming hybrid, experiential spaces. Neural interfaces do more than linking systems—actively transform the self. This transformation can be traced empirically through the *Sense of Embodiment*: the interrelated triad of self-location, agency, and body ownership (Kiltner et al., 2012). Extending further, *multi-embodied agents*—hybrid entities spanning physical and virtual domains—show adaptive embodiment dynamically aligns presence, behavior, and context. *Cognetics*, a discipline where bodily awareness meets robotics, provides a framework for exploring cognition and consciousness within such hybrid systems (Rognini and Blanke, 2016; Bransky et al., 2024). Framing neurotechnologies as *Complex Adaptive Systems*—dynamics that cross boundaries and evolve through closed-loop feedback and co-adaptation—offering a conceptual and computational foundation to model, optimize, and predict neuroprosthetic embodiment. Neuroprosthetics are co-evolving companions, striving for equilibrium with their users. Design priorities must shift from mechanical precision to personalized resonance, and therapy from task-based drills to intentional, expressive engagement. This recognition opens

pathways to resilient, individualized interventions. Equity deepens this ethical vision. Presence matures into coherence when it extends beyond mechanical performance and survival toward shared moral ground. Neuroprosthetic embodiment draws on expressive, resonant gestures, encoding raw movement into belonging, while standardization of designs risk alienation. Rehabilitation must move beyond device access and function to reclaim one’s embodied individuality alongside physical capacity. Through expressive engagements, repetitive drills become meaningful resonance, bridging function, intention, and self-expression. Enriched by cultural context, communicative gesture interactions not only enhance the daily use of neuroprosthetic and avatar control but also help restore self-narrative through embodied movement (Maimon-Mor et al., 2020; Gavette et al., 2024). In this light, embodiment emerges as both a human right and a guiding design principle. Every neurotechnological endeavor must honor bodily integrity, agency, individuality, privacy, and cultural belonging. Embodiment thus becomes the moral compass of quantum-informed medicine—aligning innovations with singular presence: restored function preserves survival, while restored coherent presence preserves humanity. To be human is to be consciously present—even as a hybrid being within technological extensions, where coherence itself becomes alive.

VII. Collapse into Quantum Presence: Life Reclaimed as Wholeness Nearly a century after Schrodinger, his vision endures: life reclaiming wholeness through uncertainty itself. *“How Quantum Is Life?”* may never yield a single, definitive answer—yet it invites us to see life as an ongoing negotiation between uncertainty and coherence. Life is neither wholly classical nor purely quantum; it is complexity incarnate—a dynamic equilibrium transforming uncertainty into the generative substrate of coherence. Where physics speaks of coherence and collapse, biology translates these into survival strategies: functionality, adaptation, intentional action. Life operates as a coherence-making process, with consciousness as its experiential counterpart. Living systems sustain coherence through continual self-adaptation. To describe life as an artistry of coherence-making is to affirm that coherence is both physical and experiential—binding energy and awareness into a single, continuous fabric of becoming. What physics terms measurement and collapse, lived experience calls recognition and awareness—the moment stochastic micro-events stabilize into the declaration, *‘I am.’* Consciousness mirrors quantum logic. Each act of awareness is not a physical collapse but a phenomenological consolidation—the instant uncertainty crystallizes into coherent presence. Neurotechnological interfaces and neuroprosthetic embodiment bring this to life, revealing reciprocity between signal and self, where closed-loop feedback turns data into lived experience. Echoing QBism’s participatory realism, embodiment becomes a world-making act for the agent-in-the-world—a birth of new experience, a renewal of life through technology, a return to presence rather than certainty. The self-aware observer co-creates the world, just as the embodied subject co-authors experience through action and awareness. When patients reclaim not only movement but coherence itself, sensation, emotion, and cognition converge into singular, coherent presence at the threshold of consciousness. This integration completes the circle—from *becoming to being*—as the hum before presence transforms into the resonance of coherence. Uncertainty becomes the fertile substrate of presence; the artificial integrates seamlessly into the living body; a hybrid self awakens. *Her confusion fades within, as the alien limb sheds skin. Distinction dissolves—separation resolves—only belonging evolves. Out of uncertainty and fears, a hybrid self appears. Through whispers of becoming, the answer is strumming:*a **** Life is a coherence embodying, a consciousness living, a quantum presence of being.*