Techno-(Neg)-Autopoiesis.
Understanding-by-building Life, Death, and their Entanglement

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Abstract

In the context of understanding-by-building research, we introduce *techno-(neg)-autopoiesis* as an original conceptual framework to explore the entanglement of life and death in artificial systems. This perspective extends ALIFE's interest in *life-as-it-could-be* by explicitly treating mortality as a generative property. We address three levels: (a) *design* — principles for embedding life and death in synthetic agents; (b) *ecology* — the ecosystems in which these processes unfold and reorganize; and (c) *epistemology* — how modelling mortality informs our understanding of life. Drawing on the theory of autopoiesis, we argue that artificial mortal agents can both advance theoretical insight and foster technologies that integrate with biospheric and planetary self-regulation.

1. Autopoiesis and Neg-Autopoiesis

Autopoiesis, as formulated by Maturana and Varela [e.g. 1], defines living systems as self-producing networks. At the fundamental level of life – the cell, the basic and constitutive unit of all living systems – these are described as *closed networks of operations of component production* that, while continuously destroying and regenerating their components, sustain themselves as networks of operations. In this view, *autopoiesis* – the distinctive property of living systems – is an *emergent phenomenon*, arising not merely from the network itself, but from its interaction with the environment, which provides the energy and matter necessary for self-production [e.g. 2]. Maturana and Varela refer to this as *structural coupling*: a reciprocal relationship of mutual perturbations and endogenous self-regulation that maintains the interdependence between the system's autopoietic processes and the environmental dynamics.

In this view, death, although not explicitly theorized by Maturana and Varela, can be understood as the *neg-emergence of autopoiesis*: the collapse of this emergent process of self-production. It involves the breakdown of the autopoietic network and the simultaneous loss of structural coupling, leading to the dissolution of the system's material identity and a related reorganization of the broader ecological network.

2. Techno-Autopoiesis

Attempts to construct life based on the autopoietic theory, through the *understanding-by-building* (UbB) approach, have not and – as we argue – will not achieve *autopoiesis-as-it-is*. In natural living systems, autopoiesis involves a co-evolutionary history and an open-ended system-environment interaction, emerging from phylogenetic and ontogenetic processes of co-constitution between the systems and their ecological context. Synthetic systems, by contrast, are created by designers – scientists and/or artists – who configure systems and environments, together with mechanisms of interrelation, based on their interpretation of the theory, choices about the level of abstraction in its implementation, and experimental constraints [3]. On these grounds, designers act not as omnipotent originators of *autopoiesis-as-it-is*, but as *ecosystemic configurators*, crafting both the system and its artificial or hybrid ecology – a "supersystem" – in which the conditions for autopoietic autonomy are decided in advance. As a result, synthetic systems exhibit only degrees or features of living autonomy, coping with a narrow range of pre-imposed system-environment co-variations.

We refer to this distributed phenomenon as *techno-autopoiesis*: not a replication of life, but artificial enactments of living autonomy, where creators, systems, and environments co-evolve within predefined bounds. Within this UbB perspective, the thematization of life shifts from binary distinctions (living/non-living; autopoietic/non-autopoietic) to diverse, situated realizations of autopoietic principles – approximations of *autopoiesis-as-it-could-be*. Through iterative cycles of UbB – i.e., implementing hypotheses in artificial systems, testing these hypotheses through processes arising from creator-system-environment interactions, and refining them into new operationalizations [3] – what emerges are trajectories of enactments that do not replicate the evolutionary processes of natural life, but generate, explore, and evolve novel, autopoietic-inspired forms of synthetic autonomy along unforeseen evolutionary pathways.

3. Techno-(Neg)-Autopoiesis: Mortal Agents for Sustainability

If synthetic life can be understood as *techno-autopoiesis*, then synthetic death becomes its negation: *techno-neg-autopoiesis*. In the framework we propose (cf. §1), this process is construed as the breakdown of the entire structural coupling that sustains the artificial system within its ecological context, opening the way for reorganization and regeneration of the broader ecosystem. This may

manifest as unintended collapse, due to material or design flaws in techno-autopoietic trajectories, or as an explicit design strategy: a UbB approach that explores the termination of artificial autopoiesis. In all these cases, we have operationalizations of *techno-neg-autopoiesis*: the implementation of *artificial mortal agents*, inspired by autopoiesis, within UbB research contexts.

This techno-scientific process is crucial, especially in the face of current sustainability challenges. It is neither simply about identifying material errors in the construction of techno-autopoietic systems, nor merely about gaining insights into how failures of autopoiesis occur in natural systems – although both are valuable outcomes of autopoietic-inspired research on life. The key point is deepening our scientific understanding, and starting technological implementation, of the life–death entanglement central to the autopoietic perspective, where life is continuously reconstituted through death and ecosystem re-organization. As biological cells sustain themselves by destroying and rebuilding their components, higher order autopoiesis involves cycles of construction and dissolution of (mortal) agents at both multicellular and social levels. This dynamic underpins natural self-regulation and, as we argue, is indispensable to developing technologies that can participate in such processes [4, 5]. Beyond individual agents, techno-(neg)-autopoiesis also invites attention to multi-agent ecologies, where interactions among mortal systems may generate emergent patterns of adaptation, resilience, and reorganization. Such techno-(neg)-autopoietic ecosystems highlight the ecological dimension of mortality as a collective, not only individual, design property.

Learning from autopoiesis how to build technologies that integrate into biospheric and planetary self-regulatory dynamics constitutes a new, specific dimension of what we call the *Gaian Synthetic Approach* [5]. We introduced this approach as a further step in the evolution of the UbB research method, which we explicitly oriented towards (a) deepening our scientific knowledge of natural self-regulatory processes through the construction of artificial models, and (b) designing technologies that, by implementing such processes, integrate sustainably into the global ecosystem. Techno-(neg)-autopoiesis provides a relevant, concrete design paradigm within the broader Gaian Synthetic Approach, operationalizing its vision of technologies integrated into biospheric self-regulation through life–death entanglement.

4. Techno-(Neg)-Autopoiesis in Science and Art

With this Gaian orientation, techno-(neg)-autopoiesis offers a systematic framework to structure and potentiate research that, in science and art, emerges sporadically and unsystematically. We illustrate this with three cases –respectively from synthetic biology, robotics, and art – that integrate agents' life-death cycles within their ecological context, showing how mortality can operate as a structural and generative property in artificial systems.

We begin with wetware synthetic biology, where *Chemical Autopoiesis* [6] – a research program focusing on bottom-up investigations of autopoietic synthetic cells – is implicitly yet closely aligned with our approach. A conceptually relevant study explored how a fine balance between concurrent anabolic (building up) and catabolic (breaking down) chemical reactions decisively determines the fate of autopoietic fatty acid vesicles [7]. Similar principles inform recent synthetic cell research [8]. In nanomedical contexts, synthetic cells have been envisioned as "nanofactories" [9] with control mechanisms – "kill switches" – to initiate autolysis once their task is complete. Such implementations operate within a UbB framework, experimentally probing how life-death dynamics can be productively embedded and regulated in artificial agents.

A robotic example resonating with techno-(neg)-autopoiesis is *Apoptotic Robotics* [10], where embodied agents are designed to model biological apoptosis – programmed cell death – as a structural property of the system. In these multi-robot systems, each unit 'dies' by default (a design condition analogous, in thermodynamic terms, to the loss of endoergonic processes in Chemical Autopoiesis) unless it receives continuous 'stay-alive' signals from the environment or other agents. This approach implicitly operationalises UbB regarding the life-death relation: mortality is embedded in physical agents to examine how programmed death shapes stability, adaptability, and resource dynamics. In swarm experiments, removing malfunctioning or redundant units prevents performance degradation, frees resources, and fosters redundancy strategies that increase group resilience. Here, neg-autopoiesis is not a flaw but a deliberate constraint, used to model and test life-death dynamics in artificial ecologies.

An artistic expression of techno-(neg)-autopoiesis resides in Theo Jansen's *Strandbeest*, wind-powered kinetic sculptures built as artificial organisms evolving with their niche and embedding mortality as design parameter [11]. Their life–death cycle, framed as both aesthetic and ecological principle, results in mortal-like machines and recursive, context-attuned forms of techno-(re)generation.

5. Outlook

The techno-(neg)-autopoietic framework positions mortality as a structural and generative property of artificial agents. Integrated within the Gaian Synthetic Approach, it links the introduction of mortal agents, on one side, to the challenge of embedding technologies within planetary self-regulation, and, on the other, to the advancement of scientific understanding of the life–death entanglement. On these bases, techno-(neg)-autopoiesis provides a transdisciplinary paradigm with relevance across ALIFE domains – from synthetic biology and robotics to artistic practice – opening new pathways for *life-as-it-could-be* research and application development.

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