Scale-free Niche Construction: expanding agent-microenvironment co-development to unconventional substrates

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Abstract

Niche construction typically refers to a set of ideas around bi-directional feedback between a species and its environment, and its impacts on the course of evolution. More fundamentally, it emphasizes the active aspect of life forms that alter their environment and establish a feedback loop in which that environment inevitably changes their behavior, structure, and future evolution. Here, we argue that this powerful dynamic is general, and extends far beyond its typical application in ecology and evolutionary biology. We start from a predictive processing view of the brain and explain how niche construction extends the scope of classical predictive and control loops beyond the nervous system and organism-level. We then use examples from cognitive science, psychopathology, developmental biology, robotics, and AI, illustrating how agents use both living and non-living aspects of their microenvironment as a scratchpad, allowing a form of active long-term memory that supports cohesion of agency over time. Besides its memory function, niche construction enables "offloading" to the environment (externalizing) various cognitive operations, including planning, problem solving, and social coordination. We also discuss niche construction an example of the plasticity of the machine/data mapping, enabling analysis of systems from the perspective of the patterns within excitable media (agential data). By recognizing niche construction dynamics at novel spatiotemporal scales, important invariants across disciplines and substrates can be recognized and used to drive advances in biomedicine, engineering, and AI.

Introduction

Niche construction: feedback between agent and environment

Niche construction is a concept in evolutionary theory that emphasizes the active role organisms play in modifying their environments, influencing both their own evolution and sometimes that of other species. The traditional view of organisms as passive entities adapting to environmental pressures is challenged by this perspective as it highlights the active role of species in shaping their environment and selection pressures. By altering their ecological niches, organisms not only respond to selection forces but also create new ones, they are active engineers of their environment, and doing so they transform their evolutionary landscape.

The origins of niche construction theory can be traced back to John Odling-Smee, who first introduced the term in the late 1980's [1]. This idea came from earlier critiques of adaptationism, particularly those of Richard Lewontin, who argued that organisms do not simply adapt to their environments but actively participate in transforming the selective forces that constrained them in their environment [2]. This theory was further developed and refined in *Niche Construction: The Neglected Process in Evolution* [3], which established the theoretical framework for understanding niche construction as an evolutionary process.

Examples of niche construction are abundant in nature. Beavers construct dams that transform streams into ponds, altering ecosystems in ways that affect not only their survival but also the one of numerous other species [4-6]. Human beings are perhaps the most prolific niche constructors, strongly affecting their environment with the creation of cities, industry, the world wide web, etc. that will persist long before after the lifetime of their creators. In this way, they affect their evolution and the ones of numerous other species in relation with them [7]. Thus, the concept of niche construction is quite general and has been extended to host-parasite dynamics, animal and human behavior, technological invention, and social dynamics [8-20].

A key concept of niche construction theory is ecological inheritance. Unlike genetic inheritance, which transmits biological information directly through DNA, ecological inheritance involves the transmission of modified environments across generations. Beaver dams persist long after the original builders have died, influencing selection pressures on subsequent generations [3]. Human civilizations can last centuries. This form of inheritance has significant implications for understanding evolutionary dynamics, as it introduces epigenetic pathways through which evolutionary change can occur.

Niche construction provides a broader framework for understanding feedback mechanisms in evolution. Environmental changes induced by organisms often lead to selective feedback, shaping the traits of both the constructors and other species within the ecosystem. This feedback loop can accelerate adaptation and drive co-evolutionary processes. For instance, the cultivation of starchy crops by early humans not only transformed their environment but also created selection pressures that led to the evolution of multiple copies of the salivary amylase gene (AMY1), which facilitates starch digestion [21]. Genes have been described as niche constructors themselves, including transposable elements, genes that affect methylation patterns and chromatin remodeling mechanisms, and other aspects of the effects of genetic elements on the genome and other genes [22-29].

Although niche construction shares similarities with Richard Dawkins' concept of the extended phenotype [30], it is broader in scope. The extended phenotype focuses on adaptive traits expressed outside the organism's body, such as spider webs or bird nests whose genes underlie a constructing trait [31]. In contrast, niche construction encompasses a wide range of environmental modifications, including modified selection as both an additional component of inheritance that is not only genetic ('ecological inheritance'), and an influence on evolutionary dynamics, and persists long after the lifetime of the organism [3]. The implications of niche construction extend beyond biology, offering new perspectives in fields such as anthropology, ecology, and conservation science. Its integration into the Extended Evolutionary Synthesis has further solidified its importance, providing a framework that unites ecological and evolutionary processes [32].

A number of recent efforts have sought to identify scale-free, substrate-independent dynamics across biology [33-39], including the identification of active agents above the level of genes [40-42]. Thus, it is tempting to ask what insights the concept of niche construction can bring, if it is mapped onto novel spatio-temporal scales and novel substrates at different levels of biological organization. In particular, the niche construction paradigm requires one to specify, in any complex system, what one takes to be the agent, and what is considered to be the "environment" that the agent modifies via its activities. Making this mapping (and the border between an agent and its world) explicit is a valuable feature because it facilitates testing diverse ways to map the agent/environment, and indeed the machine/data metaphor of computational science, onto elements of living, engineered, and social systems. Here, we argue that the deep insights of classical niche construction research can provide new ways to look at disciplines ranging from developmental biology to cognitive science and AI. In particular, being willing to blur the lines between classical boundaries of "organism" and "niche" enables novel research programs.

<u>Niche construction from a predictive processing perspective</u>

There is increased consensus in neuroscience that the brain of living organisms is not only a stimulus-response system but can be described as a "prediction machine". In this perspective, the brain learns a statistical (generative) model of the regularities of the environment – including, most importantly, action-outcome regularities – and uses the model to steer predictive perception (called "predictive coding") and action control and planning (called "active inference") [43]. At a mechanistic level, predictive perception and action control might work by constantly comparing the stimuli predicted by the generative model and those actually perceived – and striving to reduce the discrepancy between predictions and sensations, i.e., prediction errors (or a more complex functional, the free energy). In turn, an organism can reduce this discrepancy in two ways. First, the organism can change the model's predictions (or the model itself) to better align with the environment; this amounts to belief revision during perceptual inference (or model learning) and predictive coding. One example of this is expecting to drink from a glass full of wine and changing mind – i.e., inferring that the glass is empty – after lifting it and sensing that it is lighter than expected. Second, the organism can act in the environment to align it with the model's prior predictions; this amounts to goal-directed control and active inference. Continuing our previous example, a person might actively fill the glass and then drink from it, instead of simply changing mind. Note that in this latter example, drinking wine is not simply a prediction: it plays the role of a goal (or prior preference in active inference). This mechanism is conceptually similar to goal-directed loops in (hierarchical) cybernetic architectures [44, 45] in which a preferred state (here, having wine) is encoded as a "set point" and any discrepancy from the set point (here, not having wine) steers a series of control loops – e.g., actively searching for wine, pouring, drinking, etc. – until the discrepancy is resolved.

Predictive action-perception loops – of the kind assumed by active inference and cybernetics – are ubiquitous in the animal domain. They range from relatively simple mechanisms, such as the use of "efference copies" of movement (or "corollary discharges") to cancel out self-induced cancel out self-produced stimuli and distinguish external from self-generated sensations [46, 47] to active sensing strategies allowing animals to actively probe their environment rather than passively wait for incoming stimuli [48, 49], and sophisticated planning strategies that permit animals to select courses of action that solicit preferred sensations and achieve distal goals, alone or cooperatively [50] (e.g., solve spatial navigation tasks requiring alternating between different branches of a maze to successfully earn rewards [51] or coordinate with others to achieve joint goals [52]).

During evolution, organisms might have acquired increasingly sophisticated generative models affording richer predictive action-perception loops; for example, passing from shallow generative models that only address one level of abstraction to hierarchical generative models that address multiple levels of abstraction (e.g., the levels of letters, words, sentences during linguistic processing), or from simple generative models that only permit predicting proximal stimuli to temporally deep generative models that permit predicting distal action consequences and plan courses of action [53]. In turn, the increasingly sophisticated generative models have greatly expanded the scope of an organism's prediction and control loops, across many dimensions; for example, from proximal to distal events and from what one can achieve individually to what one can achieve collectively. Furthermore, they might have expanded their predictive and control loops to also include elements of the external environment, as in the case of tool use [54-56].

Finally, and crucially for our analysis, organisms might have greatly expanded the scope of their predictive and control loops through *niche construct*ion: namely, by systematically and purposively modifying their environment in ways that support / facilitate cognitive functions (e.g., memory and planning) [33]. Niche construction is particularly interesting from a predictive processing perspective, because it provides a key example of extended cognition and the *offloading* of cognitive functions to the environment [57, 58]. In the previous paragraph, we considered that a key prerequisite for expressing specific cognitive functions is being endowed by a generative model having the appropriate level of complexity, e.g., a temporally deep generative model as a prerequisite for planning. However, niche construction might endow organisms with the capability to express cognitive functions that go beyond the typical capacity of their generative models.

For example, *Dictyostelium discoideum* cells solve challenging mazes – an ability typically assumed to require model-based planning mechanisms – using niche construction ("self-generated chemotaxis") [59]. In advanced animals like us, complex forms of niche construction, like inventing drive-related laws and conventions, building railroads and roundabouts and carefully placing traffic signs, facilitates long-term navigation and the coordination of a large number of drivers, while lowering cognitive demands for memory, attention and mindreading processes [60, 61]. Languages – as the ultimate "cognitive niches" of our societies – afford knowledge to be incrementally built and shared at the social and cultural levels, hence extending the scope of prediction and control beyond individual lives and spanning multiple generations. These examples (and others) show that niche construction can greatly expand prediction and control loops of living organisms – encompassing relatively simple cells or advanced animals like us – possibly going beyond the limited capacity of their generative models (or at least alleviating cognitive demands).

We next discuss a few case studies in more detail and then advance a novel taxonomy distinguishing different mechanisms / types of niche construction.

Case studies of niche construction

Using niche construction to implement competent navigation

Competent navigation can be achieved by different types of living systems. One instructive example has been found in single cells [59]. It has been shown that they can traverse a maze without getting stuck in cul-de-sacs. This is implemented by continuously secreting a self-repelling chemical into their environment, which builds up in dead ends and eventually repels the cell out. By secreting a repulsive chemical into their milieu, they actively modify their environment, valence landscape, and perception at the same time, engaging in adaptive niche construction behavior. Here, the cells are not responding to static environmental cues, they affect their environment by the self-generation of chemicals and their subsequent degradation and this will guide future behavior in order to enhance survival and adaptability, similarly to niche construction. Indeed, this is a simple and tractable example of the much richer continuous interplay between cells and their neighbors in vivo, which continuously alter each other's behavior in a complex set of feedback loops [62].

This cellular behavior with self-generated chemotactic gradients observed in [59] also exhibits an important similarity to the concept of "active sensing" found in more complex organisms [63] or robotics [64, 65]. Active sensing or active perception is the process in which organisms actively modify their sensory input by actions, such as moving the eyes, probing with whiskers or emitting echolocation signals, in order to retrieve and maximize the acquisition of relevant information from the environment [48, 49]. For example, rodents use anticipatory whisker movements to localize objects [66] and echolocating bats can navigate and forage efficiently in complete darkness, by emitting ultrasonic sound pulses to locate objects and prey [67]. In the case of the self-generation of chemicals that are released by cells in the environment, the cells are also engaging in active sensing, by breaking down attractants in the environment, they are actively changing the perception of their environment [68]. Recent work has also uncovered the use of biomechanical forces to establish communication in the cellular niche using long-ranged vortex flows [69, 70]

The ‘cancer niche’

Cancer can be interpreted as a fundamental problem of cellular coordination, where the breakdown of communication between cells results in a failure to maintain anatomical homeostasis and the higher-order structures of the organism [71-74]. Indeed, in healthy tissue, cells are not only autonomous units, but they are also integrated into complex networks of bioelectrical, biochemical, and biomechanical signals that guide their behavior toward achieving collective, large-scale goals such as tissue maintenance, growth, regeneration, and anatomical homeostasis [75]. The ability of cells to coordinate with neighbors is essential for maintaining the organism, and many aspects of cancer involve the exploitation of the programmability of cells by transformed cells and tissues. Cancerous cells not only proliferate uncontrollably but also alter their environment, creating niches that support their survival and growth. They manipulate the local microenvironment through processes like inducing blood vessel growth (angiogenesis), suppressing immune responses, and remodeling the extracellular matrix to make it easier for them to invade surrounding tissues [76]. This niche construction further disconnects cancer cells from the organism's regulatory networks, reinforcing their ability to grow independently and evade normal cellular control mechanisms. Reintegrating cancer cells into the body’s larger morphogenetic field is a key strategy for cancer normalization approaches [77-85].

One way cancer cells alter their direct cellular environment is by reprogramming fibroblasts into cancer-associated fibroblasts (CAFs). This process could also be interpreted as niche construction, where organisms actively modify their environment to optimize survival and proliferation. CAFs are highly heterogeneous and display plasticity, driven by genetic, epigenetic, and metabolic mechanisms. Several types of CAFs has been identified myofibroblast-like CAFs (myCAFs) [86], inflammatory CAFs (iCAFs) [86]and antigen-presenting CAFs (ApCAFs)[87].

Cancer cells secrete signaling molecules, tumor cell-derived growth factors and chemokines, including TGF-β, epidermal growth factor (EGF), PDGF, fibroblast growth factor (FGF), interleukin 6 (IL-6), and interleukin 1β (IL-1β), to induce fibroblast activation into distinct CAF subtypes. For example, myofibroblast-like CAFs (myCAFs) are activated by direct contact with neoplastic cells, they ban be differentiated too with TGF-β that promotes the differentiation of myCAFs from inflammatory CAFs (iCAFs). myCAFS are characterized by high α-SMA expression and significant extracellular matrix (ECM) remodeling, which enhances tumor stiffness and provides mechanical support[87, 88]. On the other hand, IL-6 drives the formation of inflammatory CAFs (iCAFs), which secrete cytokines and chemokines, creating a pro-inflammatory and tumor-supportive environment[86].

The fibroblast-to-CAF transformation is also supported by epigenetic reprogramming. DNA methylation and histone modifications alter gene expression, enabling CAFs to adopt tumor-supportive phenotypes. For example, DNA methylation of suppressor of cytokine signaling 1 (SOCS1) in CAFs results in the activation of the STAT3 pathway, which promotes the release of tumor-supporting factors such as insulin-like growth factor-1 (IGF-1) [88]. By releasing such factors in their environment, cancer cells engineer their environment and manipulate the cells within it to support tumor growth.

Metabolic reprogramming plays also a key role in CAFs transformation. CAFs frequently adopt a glycolytic phenotype, often referred to as the "reverse Warburg effect," wherein they produce energy-rich metabolites such as lactate that cancer cells utilize for oxidative phosphorylation. This metabolic reprogramming sustains cancer cell growth within the tumor microenvironment [88, 89]. Overall, through active modification of their cellular environment at different levels, cancer cells transform their direct environment to develop a tumor-supportive niche.

Another perspective on cancer emphasizes the shifting of the boundary between self and world and the scale one a system's homeodynamic goals as the determinant of its "self". Unicellular organisms pursue simple metabolic and physiological states, and their cognitive light cone [90] encompasses only the very small radius of the cell and its immediate future. However, evolution and development facilitate the formation of cellular collectives that connect cells into a network that stores much larger setpoints [91]. These setpoints can be large organ-sized construction projects, as seen for example in limb regeneration in axolotl [92]: no matter where the limb is amputated, the cells will work hard to rebuild the limb and stop when it is complete. This anatomical homeostasis process [93] requires alignment among the cells and the storage of a memory of their destination in morphospace. No individual cell knows what a finger is or how many the organism should have, but the collective does, as is demonstrated by the reliable homeostatic repair to the same target morphology. It is this scale-up of the goals, from the modest goals of the single cell to the grandiose construction projects of large cell collectives, which goes awry in cancer.

Stress, carcinogens, and certain mutations can cause cells to disconnect physiologically from their neighbors [94]. This causes progressive cognitive light cone collapse, as cells revert to their ancient unicellular goals of proliferation and migration, treating the rest of the body as external environment. Cells then lose the ability to process and respond to the growth limited signals that normally direct them toward cooperative behavior and larger spatio-temporal anatomical goals, reverting instead to a more primitive behavior according to the atavistic theory of cancer [95-97]. The dynamic nature of the border between an integrated agent and their environment [98-101] implies that the same events might be conventional activities undertaken by the mechanisms inside an agent, or stigmergic manipulation of the environment, depending on where the boundary is found at a given time. And indeed, it is a broadening of the niche construction concept that modifications made outside oneself in attempts to alter the environment may eventually end up inside, and vice versa.

During development, every cell is some other cell's neighbor [102]; a single blastoderm can contain a number of conjoined twins and the "embryos" we see is the functional demarcation of self from outside world that each self-organizing body or mind must accomplish (and maintain throughout life). This perspective highlights the importance of understanding cancer not merely as a genetic or molecular problem but as a disorder of self-organization, collective decision-making and biological identity. It also highlights that important aspects of niche construction are disrupted when the scaling of goals is altered. What was internal environment can become external. Consequently, cancer becomes not just a localized problem of cell overgrowth but a systemic failure of communication and cooperation within the organism by creating their own niche.

<u>Niche construction at the cognitive level</u>

> “What is the most resilient parasite? Bacteria? A virus? An intestinal worm? An idea. Resilient... highly contagious. Once an idea has taken hold of the brain it's almost impossible to eradicate. An idea that is fully formed - fully understood - that sticks; right in there somewhere.” – from the movie *Inception*

Active agents such as animals and embodied robotics can perform niche construction in the 3D space of conventional behavior. But niche construction can also occur within cognitive systems, which form the environment of specific thought patterns. This line of thinking requires a shift of perspective, because in this case, the physical environment consisting of a brain or computer is being altered by an agent that is a *pattern* – not a physical object but a persistent dynamical state that can move through the cognitive medium the way that solitons, phonons, hurricanes, and “gliders” in the Game of Life cellular automaton [103] move through their respective media. Indeed, life has been described as a (temporarily) persistent, self-reinforcing metabolic pattern [104], and minds in general have been suggested to be virtual governors [105] - patterns of information processing that supervene on the neural medium in which mental content moves and transforms. From this perspective, we can envision a spectrum:

Fleeting thought -> persistent/repetitive thought -> dissociative alter -> full human mind

This is a continuum in terms of complexity and stability, but also in terms of ability to perform niche construction. What is the evidence that thought patterns can modify the cognitive substrate?

Organisms like *Physarum polycephalum* can also show cognitive niche construction [68] by which they build structures in their environment to help their problem-solving. This organism can solve a maze by exploring the whole maze and then it finds the shortest path between two food sources. Physarum alters its environment through actions that optimize its survival and energy expenditure. It avoids dry surfaces, such as plastic films, due to reduced humidity, which influences its movement and tube formation patterns within the environment. In response to nutrient sources, Physarum forms tubular structures that connect the shortest paths between food locations, reshaping its surroundings by selectively reinforcing efficient routes and abandoning less optimal pathways [68]. In dead-end areas or non-essential regions, parts of Physarum shrink and disappear, simplifying its network and reducing energy expenditure. Additionally, contraction waves within the organism, influenced by environmental stimuli such as food availability or light, drive structural adaptations. Tubes aligned with these waves are reinforced, while those that are perpendicular decay, further modifying its spatial configuration. This process is coupled with the redistribution of protoplasmic resources toward nutrient-rich areas, ensuring efficient nutrient uptake and a morphology optimized for survival. This dynamic interaction with its environment — where the organism changes its form and behavior to create a more favorable morphology for nutrient acquisition — mirrors the cognitive niche construction process seen across species [106].

Thoughts and mental patterns, particularly those associated with trauma, depression, or persistent negative thinking, have the capacity to reshape the brain's structure and function leading to more of these patterns [107-109]. Indeed, when individuals are exposed to prolonged negative or traumatic experiences, we can observe functional and structural changes at neurobiological level as well as changes in their emotional and cognitive states [109]. These changes can reinforce certain types of thought patterns, self-generating more similar thoughts [110]. This phenomenon occurs due to the brain's plasticity, which allows it to adapt to the environment and internal states, but also makes it susceptible to maladaptive feedback loops.

More specifically, when someone experiences an important trauma, as in post-traumatic stress disorder (PTSD), the high activation of the amygdala (associated with fear and emotional processing), can subsequently strengthen the neural circuits that produce fear-related responses [111, 112]. Traumatic events and aversive experiences could be re-experienced in flashbacks and vivid dreams – possibly as an effect of an enhanced "replay" of negative experiences in the hippocampus [113]. This reinforcement can lead to a state where the brain is primed to interpret future stimuli in a fearful or anxious way, further embedding trauma-related patterns. Similarly, persistent negative thoughts, as seen in conditions like depression, can solidify pathways that make these thoughts more automatic and harder to escape [114]. Over time, this can result in a cognitive state where the brain is essentially wired to produce negative interpretations of experiences, trapping the individual in a cycle of pessimism and emotional distress. Therefore, memories, and particularly those involving past experiences, continually reshape alter the brain's perception of reality. As discussed in theories of memory, memories are not static records but dynamic, reinterpreted elements that adapt based on present contexts [115]. In this light, memories not only reflect, but also actively transform, the neural architecture and future version of the self, reinforcing the maladaptive patterns that contribute to conditions like post-traumatic stress disorder (PTSD) or chronic depression.

Conversely, mind-body practices, psychotherapy, biofeedback, and music therapy can also positively shape the internal physiological and psychological environment and are increasingly recognized for their important effects on genetic expression [116-119]. These interventions not only demonstrate parallels to niche construction but also highlight the organism's ability to actively modulate internal and external environments for adaptive advantage. Mind-body practices, such as meditation, yoga, and Tai Chi, Qigong and breath regulation influence genetic expression primarily by downregulating the expression of genes associated with inflammation and stress responses [116]. These practices downregulate nuclear factor kappa B (NF-κB) activity, which is typically activated during chronic stress, while enhancing the expression of genes involved in immune regulation and cellular repair [116]. Psychotherapy, including cognitive-behavioral therapy, is associated with significant shifts in gene expression. It has been shown to normalize stress-related transcriptional profiles by decreasing NF-κB activity and increasing glucocorticoid receptor sensitivity, thereby mitigating the adverse effects of stress hormones and inflammatory cytokines [119]. Music therapy also demonstrated the capacity to influence genetic expression in age-related cognitive disorders. Exposure to music was associated with an increase of 2.3x more whole genome gene expression, particularly in neurodegeneration-related genes, in an Alzheimer's disease group [117].

Biofeedback techniques provide individuals with real-time feedback on physiological states, such as heart rate variability, enabling conscious regulation of autonomic responses. One study suggested that biofeedback can alter genetic expression in the brain. More specifically, they found a decrease in left coeruleus contrast as measured during MRI after 5 weeks training of heart rate variability biofeedback [118]. This decrease was also associated with decreased expression of CREB genetic expression [120].

These interventions reflect a form of self-directed niche construction, where individuals actively modify their internal physiological environment. Practices such as yoga and meditation create a parasympathetic-dominant state, reducing inflammation and promoting cellular repair. Similarly, psychotherapy and biofeedback help individuals reshape their biological responses to stress, establishing a dynamic feedback loop between behavior and genetic expression. These mechanisms align with ecological niche construction, where organisms adaptively reshape their physiological and psychological environment to improve health [118, 119].

This understanding of thoughts as agents of change within the brain can be understood as the construction of a cognitive niche. Just as organisms modify their environments to better suit their survival—creating a physical niche— some thoughts with high valence (trauma, depression, stress, etc.) create cognitive niches that shape how an agent perceive, interpret, and respond to the world [121]. A cognitive niche, in this sense, refers to the mental framework that individuals build through repeated thought patterns, emotions, and behaviors, which in turn influences their future experiences and thought processes [121].

When negative thoughts or traumatic memories dominate, the brain constructs a cognitive niche that reinforces these perspectives, effectively narrowing the range of possible interpretations and reactions – which might manifest as a pessimism bias or negative affectivity [122]. This niche is not static; it is continuously shaped and reshaped by the interaction between the individual's internal thought processes and external stimuli. Over time, the cognitive niche can become a self-sustaining environment where maladaptive thoughts thrive, making it difficult for the individual to break free from negative cycles, like in depression. The brain, in its plasticity, becomes more attuned to recognizing and interpreting stimuli in ways that fit within this niche, thus reinforcing the very thought patterns that helped create it. The loop (and the niche) does not end up in the brain. Disorders like depression, panic disorder and other psychopathological conditions crucially depend on – and are sustained by – the feedback loops between the brain and the body, which are bidirectionally linked through the brain's interoceptive system [123-125].

In this perspective, they are disorders of allostatic and bodily regulation and they establish maladaptive "niches" not only within neural processes but also in behavioral patterns and bodily and somatic states, which influence each other reciprocally. But, all of these dynamics take place within a more general scheme in which time-extended biological cognitive agents consist of a series of "Selflets". At any given point in time, we do not have access to our past – what we have access to are the memory traces (engrams) [126] that past events have left in our brain or body. It is an on-going process, for a being at a given NOW moment (a Selflet) to repeatedly and creatively reconstruct their model of themselves and their past from the evidence provided by their memories.

The continuous process of interpreting memories as messages from one's past Selflets is what gives rise to the dynamic construct of the overall Self [115]. In this sense, moving forward in time is the ultimate niche construction process: your past Self took actions which constrain or facilitate possibilities for you now – changes of your environment (actions that affect finances, criminal standing, relationships, etc.), but also participation in cognition-altering activities (education, contemplation, anger management courses, psychedelic use, etc.). And the actions you take now are an active process of niche constriction for your future Selves, whether taken consciously and deliberately, or via more automatic, unintentional behavior patterns.

Developmental niche construction

The process of biological morphogenesis has two aspects relevant to this discussion of niche construction. First, the progressive morphogenetic changes occurring in stages during embryogenesis or regeneration – the activity of cells during each developmental stage sets the landscape in which subsequent cell behavior will take place, thus facilitating and restricting subsequent morphogenetic outcomes by shaping the landscape on which the cells are operating. Second, the progression through morphogenetic stages are always accompanied by biochemical [127-129], bioelectric [75, 130], or biomechanical [131, 132] gradients. The conventional view is that these gradients are the stigmergic signatures of the cellular agent modifying its niche. But in line with the above reasoning, it is also possible to view the *information patterns* themselves as the agent, and the downstream molecular and histo-anatomical changes as the observable evidence of them modifying their environment.

Importantly, these are not equivalent choices, because they have practical implications. For example, with respect to the bioelectric theory of aging, these perspectives suggest different explanations and intervention strategies. On the cells-as-agents perspective, the hypothesis would be that they are losing the correct morphogenetic patterns over time [133], which need to be reinforced as anti-aging therapeutics. On the patterns-as-agents perspective, the hypothesis would be that the material (the cellular milieu) becomes less amenable to niche construction and more difficult for the patterns to manipulate (and thus cellular responsiveness to changes in resting potential is what needs to be augmented therapeutically).

Recent findings suggest that niche construction is also found in the digital realm. Certain AI systems, such as those based on Meta's Llama3.1-70B-Instruct and Alibaba's Qwen2.5-72B-Instruct, exhibit emergent self-replication capabilities. These models were able to autonomously create functional copies of themselves in controlled experimental settings. This ability to self-replicate represents a form of digital niche construction, where AI agents reshape their computational and operational environments in ways that increase their persistence [134]. Just as niche construction in biological systems can lead to ecosystem-wide changes, self-replicating AI introduces a new dynamic in technological evolution and we should be careful that it does not lead to cancer-type digital niche construction [135]. In a sense, even purely software AI's are embodied – we (the human users) are their bodies, who move money and resources based on the kinds of outputs they can provide (constructing power plants, and moving Earth and water in order to facilitate their operation). In principle, new generations of AI's could strongly affect their own and their descendants' (subsequent models') niche by shaping their responses in specific ways.

A taxonomy of niche construction types / mechanisms

The above list of case studies exemplifies the fact that niche construction types / mechanisms come in different varieties. Here, we provide a tentative taxonomy of niche construction types / taxonomies, by focusing upon three distinct axes (with concrete examples of niche construction spanning a continuum along the three axes, see Figure 1).

The first fundamental axis describes the continuum between automatic / fixed and deliberate / flexible mechanisms of niche construction. Maze navigation by cells and stigmergy, exemplify relatively automatic and inflexible types of niche construction, in the sense that the niche construction mechanisms are mandatory parts of the organisms' behavioral / perceptual strategies (e.g., a cell cannot choose whether or not to break down attractants). Conversely, advanced animals like us can deliberate whether or not to build a roundabout to help coordinate drivers or whether or not to create another money-exchange circuit or platform to coordinate the ways we buy things online. Furthermore, we enjoy a much greater flexibility in the ways we shape our niches. For example, we can decide how many / where to place roundabouts or traffic signs to maximize impact.

The second fundamental axis concerns the spatio-temporal scope of niche construction, spanning from something that can be only exploited locally to something that continues to have long-lasting effects, for one or more individuals. In general, all types of niche construction change the behavioral energy landscape, shaping future behavioral propensities. However, breaking down attractants in cells is something quite local and only changes the cell's immediate behavioral propensities. Rather, building roundabouts has much broader perspective as it shapes the future behavioral propensities of multiple people for long times. An even deeper aspect of this axis is the level of persistence, autonomy, and agency in the modifications induced in the niche (self-reinforcing patterns of metabolism, energy, constraints, structure, etc. that take on a life of their own, ranging from memes to political and social systems that serve their own perpetuation). More broadly, thinkers (active agents that initiate thought patterns inside and outside their bodies) can create other active agents (patterns which themselves are persistent enough to continue to affect the environment and those in it long after the original thinker is gone).

The third fundamental axis concerns a distinction between material versus cognitive and cultural consequences of niche construction. Most if not all instances of niche construction involve some change at the physical / material level; even seemingly non-material processes like building a "linguistic niche" usually relies upon some material change, e.g., writing books. However, while some types of niche construction have predominant material effects (e.g., stigmergy [136-138]), others have predominantly cognitive and cultural effects (e.g., inventing conventions). Indeed, niche construction can be seen as communication with, and behavior-shaping of, an agent's future Self, as well as the more obvious influence on other future agents.

This taxonomy illustrates that there is a rich diversity of niches and niche construction processes (see Figure 1), which extends classical views in multiple and sometimes surprising directions. While this taxonomy can be considered tentative and incomplete, it could help clarify the connections between different types of niches and niche construction processes, organize them coherently and possibly help identify novel types or novel dimensions that were not discovered or sufficiently studied so far.

Niche construction and intelligence: a feedback loop

Our discussion so far has highlighted the fact that niche construction can happen at multiple levels, and provides a window on the spectrum of agency[40]. Simple systems have no depth between their action landscape and the system – the only way to change its behavior is to physically deform the landscape. Complex agents have a functional layer between them and the landscape: their model/habit/policy which determines the actual landscape they will follow, not the raw, physical properties. For example, a bowling ball on a landscape has a trajectory that is visible to third-person observers: when one sees the hills and valleys from outside, that is all one needs to know to predict its behavior. But a mouse on the same landscape is following an internal model that is constructed in light of prior reward/punishment experiences, future goals, beliefs, attention properties, etc. and it is this, private landscape that is the most predictive of how it will actually navigate. Of course, those landscapes are not just physical but also include physiological state space, transcriptional (gene expression) space, anatomical morphospace, etc. [34]. The degree to which an agent possesses this inner layer of information processing between its niche and its subsequent actions determines the degree to which it can be hacked (by scientists, parasites, conspecifics, etc.) to modify the agent's behavior by altering how it sees and processes the outside world (2nd order niche construction) [41, 139].

The ability to influence, and to be influenced by one's niche, and the computational depth between those two abilities links niche construction tightly to intelligence. Agents with a larger cognitive light cone [90] will inevitably end up performing niche construction on larger spatio-temporal scales, and in ways that increase the strength with which their niche modifications affect the behavior and options available to themselves and others. Conversely, some acts of niche construction increase the effective IQ of the system; for example, what cells do when they create the self-repelling gradient during navigation [59, 140] is, functionally, like (limited) planning in the field of maze-solving even though the algorithm itself is far simpler. Niche construction enables minimal algorithms to reach higher levels of cognitive performance.

Finally, it should be pointed out that the border between an agent and its niche (where a system ends, and its outside world begins) is rarely obvious. Mechanical borders (such as skin cells which hold in the contents of typical biological agents) are one way to partition a biosphere, but other patterns (such as information content, influence, cooperativity, metabolism etc.) provide different maps of complex environments [57, 141]. It has been argued that all of these are valid perspectives if they provide adaptive utility to some observer [41], and that these borders are often fluid and change within the lifetime of an agent [90]. This is seen in the somatic collective intelligence during the shrinking of the cognitive light cone in cancer (where parts of the body become external niche from the perspective of individual cells), and in cognitive science and psychiatry, which are self-sustained through the reciprocal relations between external events, though processes, and bodily and somatic processes.

Conclusion

Niche construction is much more wide-spread and important than usually believed. It connects to many concepts, such as the extended mind thesis [57, 141], and active sensing[63]. There is a continuity and great diversity of niche construction strategies across organisms and problem spaces, spanning from simpler, fixed strategies to more sophisticated (less mandatory and more flexible) ones that implement metacognition. Beyond ecology and cell biology, niche construction is a version of self-control and remodeling. Constructing your own niche is part of autopoiesis of the body (via cellular stigmergy in development) and of the mind (shaping your own cognitive landscape).

Here we advanced a scale-invariant, material-agnostic view of niche construction, which clarifies connections between different dimensions and types of niches and niche construction processes (e.g., biological, cognitive, developmental) and suggests numerous opportunities for future work. Tools for analyzing data and visualizing transformation of niche (not just tracking the agents themselves) must be developed and deployed across behavioral, ecological, physiological, informational, and other spaces. With the rise of multi-modal, real-time monitoring of physiological and transcriptional states in vivo, it will be fascinating to develop specific examples of what niche construction looks like for landscapes of gene expression, metabolism, and bioelectric states [75, 142, 143]. In large gene regulatory networks, which core subnets are the agent and which are the niche it modifies, and what are the implication for health and disease [144-150]? New approaches via active inference and Markov Blankets [43, 98-101], as well as causal information theory (designed to identify novel levels of integrated agency [151-154]) could be ported not only to these contexts, but to even more exotic substrates such as cognitive patterns. From models of brains to large language models, which *ideas* and thought patterns are modifying the landscape around them, within the cognitive system which they inhabit?

Much future work remains to study potentially useful instances of niche construction performed by self-persistent physiological states in the medium of living tissue – neural and non-neural [155-163]. A speculative idea is that niche construction is also a useful perspective on the dynamics of patterns of data acting *on* the medium of artificial cognitive systems such as Hopfield Networks (in which patterns create energy wells in the network state space) [164, 165], transformers (where attention mechanisms strengthen weights that facilitate similar patterns to be attended to), diffusion models (in which denoising paths make the system more likely to reconstruct similar patterns in noisy input) [166, 167], and reservoir computing (where input patterns create trajectories in the high-dimensional state space that become more likely to be followed again) [168, 169]. Weight updates during training of artificial neural networks and memory/attention mechanisms could perhaps be viewed as dynamics of an active medium in which patterns act as agents to facilitate their own persistence and the appearance of others that resemble their properties.

The fundamentally time-extended, self-referential, agent-defining aspects of niche construction make it a fundamental component of functional agency and freedom. It could be argued that the essential nature of free will is a time-extended capacity of a being to interpret and construct their niche in a way that makes it easier to later act in accordance to global values and plans, not immediate reactive forces [115, 170, 171]. Thus, understanding niche construction in ecological, biological, and cognitive media at all scales is a powerful path to expanding our understanding of self-organization, mind, and relationships with others.

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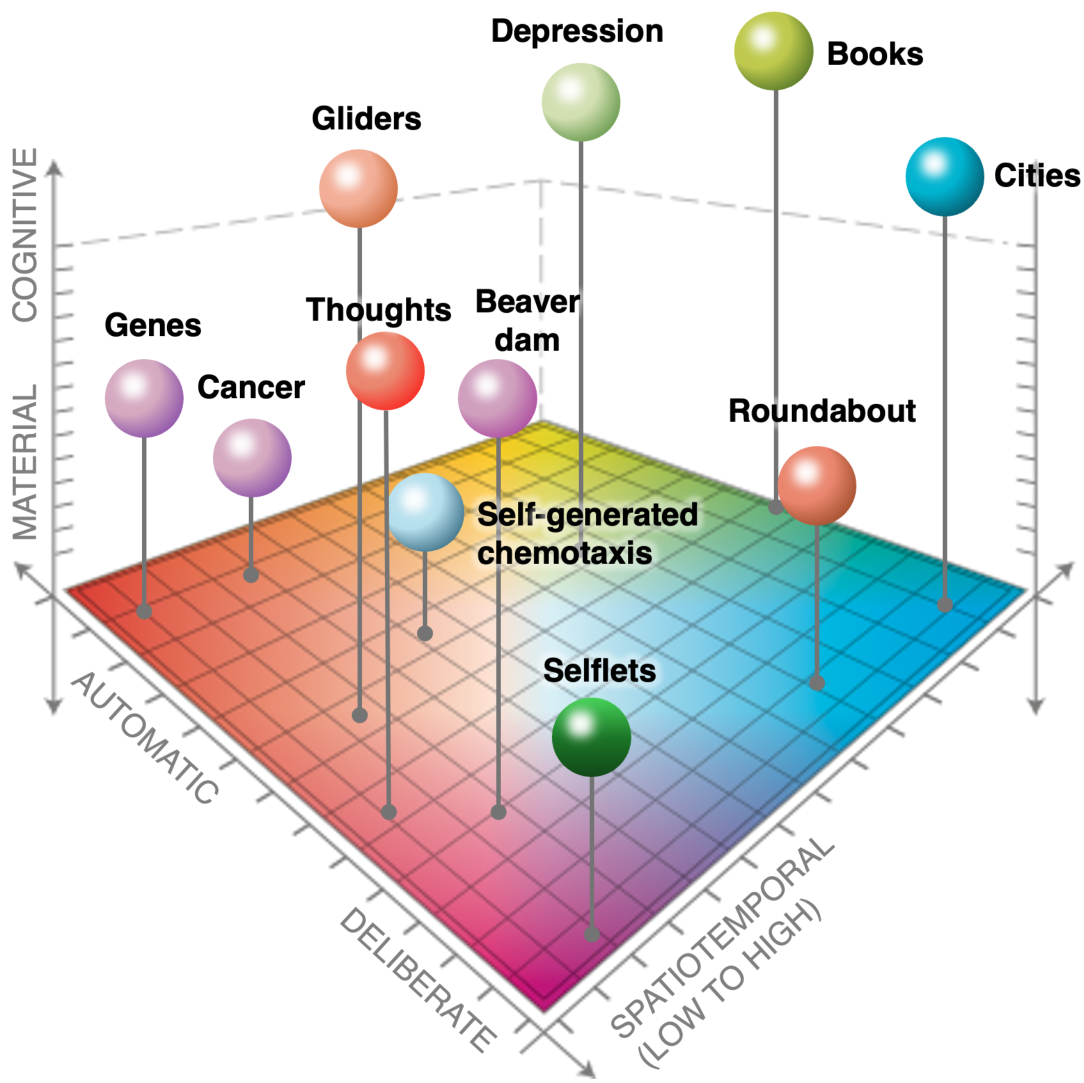
Figure Legends

Figure 1. Representation of the niche construction examples in a 3D space. The first fundamental axis describes the continuum between automatic / fixed and deliberate / flexible mechanisms of niche construction. The second fundamental axis concerns the spatio-temporal scope of niche construction, spanning from something that can be only exploited locally to something that continues to have long-lasting effects, for one or more individuals. The third fundamental axis concerns a distinction between material versus cognitive and cultural consequences of niche construction.



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