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# From Gradients to the Texture of Life Ecological Realism as a Research Programme

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**ABSTRACT:** This paper proposes ecological realism as an interdisciplinary research programme for understanding the material, biological, ecological, symbolic, and institutional conditions of life. It challenges the conventional separation of nature and society by examining how forms emerge, persist, and transform through processes of energy and material exchange, organisation, maintenance, repair, and reproduction. The programme is organised around the endo–exo relation, which distinguishes the internal organisation of a system from the external conditions and dependencies through which it sustains its relative identity. Tracing a stratified natural history from physical interactions and prebiotic chemistry to living organisms, ecosystems, animal cognition, language, technics, and institutions, the paper investigates how new forms of organisation and temporality emerge without losing their dependence on prior material conditions. It introduces the concepts of endogenous yet exo-conditioned time, ecological co-reproduction, exosomatic memory, and common reproduction to explain how living and social systems depend on the renewal of shared conditions. Extending this framework to political economy, the paper argues that economic activity, technological development, and institutional arrangements must be evaluated in relation to their material throughput, ecological consequences, maintenance requirements, and temporal horizons. It further develops an admissibility framework for assessing whether practices and institutions preserve the conditions necessary for collective and intergenerational continuation. Rather than reducing normative questions to biological or ecological facts, ecological realism establishes material and temporal viability as a necessary condition for their practical consideration. The paper concludes by outlining a research programme that integrates empirical investigation, conceptual analysis, and democratic deliberation while preserving disciplinary differences and historical contingency.

## 1 INTRODUCTION WHY A NEW RESEARCH PROGRAMME

The ecological crisis concerns not only emissions, biodiversity, energy, and resources, but also the picture through which modern societies understand reality. Nature has commonly appeared either as an external stock of resources and constraints or as a neutral stage for human history. Conversely, it has sometimes been reduced to a cultural construction. The first image cannot adequately explain the emergence of living, social, and symbolic forms from material processes; the second cannot explain why markets, states, technologies, and narratives cannot negotiate away their own material, temporal, and ecological conditions (IPCC 2023; IPBES 2019).

Ecological realism proposes a research programme beyond this choice. Its starting claim is that every energy process has a form, and every form exists through processes of formation, maintenance, repair, and transformation. Forms are relatively stable constraints within processes, while processes operate through boundaries, structures, rhythms, memories, and inherited arrangements. Time is internal to this relation rather than an empty container of change. The programme asks how boundedness, memory, agency, and meaning have become possible on a home planet without treating their history as an

ascent culminating in humanity.

The texture of life is a branching, nested, interrupted history. Physical interactions produce bound forms; these participate in chemistry and planetary processes; some chemical systems acquire selective compartments and self-maintaining organisation; organisms and ecosystems co-produce conditions of persistence; animals develop sensorimotor and anticipatory capacities; human communities make those conditions explicitly contestable through language, technics, institutions, and economies. No transition was inevitable. Earlier forms opened constrained but plural possibilities rather than determining later outcomes.

Texture names a differentiated, historical, vulnerable field whose strands retain relative identities through their relations. It is material before it is linguistic. Its earliest metaphorical "texts" are consequential differences retained in phase relations, molecular bonds, membranes, metabolic cycles, inherited sequences, ecological feedbacks, bodily habits, and learned responses. Language makes these relations nameable, comparable, criticisable, and deliberately reorganisable. Its logical dimension enables distinction, inference, abstraction, and counterfactuals; its associative and semantic dimension connects signs with embodiment, memory, affect, analogy, and place. Together they enlarge collective freedom while remaining materially dependent: propositions do not need sunlight, but speakers do; monetary promises presuppose labour, energy, matter, care, time, and ecological sinks (Clark 1996; Lakoff and Johnson 1980).

The principal grammar is the endo–exo relation. Exo names conditions, gradients, flows, and other systems on which a process depends; endo names organised transformations through which a system sustains relative identity, states, rhythms, and capacities. The distinction is graded. A bound physical system has characteristic states and couplings without reproducing its boundary. Cells couple membrane production, metabolism, repair, and reproduction. Ecosystems nest reciprocal dependencies.

Human beings inhabit a further exosomatic environment of language, tools, archives, law, money, and institutions. This environment is causally real but remains dependent on planetary conditions.

A parallel distinction concerns time. Physical durations, frequencies, phases, and irreversible processes do not yet constitute an organism's own time. Endogenous temporality becomes stronger when rhythms, memory, repair, and reproduction contribute to continued existence. Such time is internally organised yet externally conditioned by throughput, environmental regularities, and other beings.

Societies that deny soils, organisms, infrastructures, or persons time for renewal undermine their own reproduction (Pittendrigh 1993; Montévil and Mossio 2015).

Ecological realism therefore rejects naturalistic reduction and cultural exceptionalism. It seeks bridges among disciplines without deriving cells from particles, justice from biology, or institutions from ecology. Its commitments are real material conditions, the causal efficacy of organisation, bounded historical contingency, and normativity whose practical claims remain admissible within the conditions of life. The following sections develop this argument from form and process through natural history, living time, ecology, animal worlds, language, and exosomatic institutions to political economy and common reproduction. The shared question is how an activity depends upon, damages, or renews the texture that makes it possible.

## 2 ECOLOGICAL REALISM FORM PROCESS TIME AND THE ENDO–EXO RELATION

Ecological realism begins neither with a self-sufficient object nor with a sovereign subject. It begins with differences that make differences: gradients enable work, molecular configurations constrain reactions, membranes regulate exchange, forests alter water and carbon relations, and technical and legal systems redistribute action and risk. These are real constraints, identified through relations and processes at a specified scale. Realism concerns dependencies that do not disappear when renamed or repriced; ecology concerns their organisation through maintenance, transformation, conflict, and co-production.

### 2.1 Realism after the Nature–Society Divide

Nature and society are distinguishable without being separate worlds. Society requires metabolic exchange with soils, waters, atmosphere, other organisms, and usable energy, while also requiring language, memory, techniques, institutions, and norms. Neither fact cancels the other. Norms are not chemically deducible, and ecological time is not culturally optional. Social forms organise material relations, which can resist or undo those forms.

This realism does not assume one scale-free inventory of self-identical things. Scientific objects are identified through

instruments, models, measurements, and comparison; relevant boundaries depend partly on the question. Yet this dependence does not make rivers, cells, or atmospheres discursive inventions. Their processes can frustrate expectations and invalidate models. Relational quantum mechanics further challenges the image of self-contained bodies possessing all properties independently of interaction, while decoherence makes system–environment coupling central to effectively classical correlations. Neither provides a shortcut to a theory of life or society: relations must be established in the terms of each domain (Rovelli 1996, 2021; Zurek 2003).

### 2.2 Form as Constraint and Process as Transformation

Form means a relatively enduring constraint that alters possible trajectories, rather than geometric shape alone. Bonds, enzymes, membranes, habits, roads, property regimes, and constitutional rules can all be forms. Constraints are generative as well as limiting: riverbanks enable channelled flow; enzymes enable reliable transformations; grammar enables intelligibility; procedures enable durable collective action. Their efficacy depends on the organisation and time scale under investigation.

Process means transformation through time, including movement, reaction, growth, decay, repair, learning, labour, exchange, and institutional change. It need not be progressive. A form can likewise be fragile, temporary, contested, or dependent on activities it undermines. Inquiry must ask reciprocally what maintains or transforms a form and how that form channels subsequent processes.

Information, in the broad sense of being-in-form, is a retained, structured, consequential difference. Physical configuration is not thereby semantic meaning. Biological organisation makes differences consequential for an organism's continuation; language makes signs explicitly interpretable, negatable, fictional, and revisable. Work on organisational closure distinguishes transforming processes from relatively stable constraints and explains living organisation through constraints that help maintain one another (Montévil and Mossio 2015). Ecological realism asks how such constraints emerge, nest, persist, and break, including in institutions.

### 2.3 Endo and Exo as a Graded Relational Distinction

Exo includes energy, materials, gradients, other systems, historical circumstances, and regularities. Endo names the organisation that transforms inputs, maintains states, generates outputs, and, in stronger cases, reproduces its own constraints. Neither is an isolated substance. At a thin physical level, atoms and molecules have characteristic states and couplings, but do not actively repair their boundaries. A chemical oscillator has recurrence without necessarily possessing biological autonomy.

A stronger endo appears when internal chemistry supports a selective boundary which, in turn, channels exchanges needed by that chemistry. A cell's membrane is continually produced, repaired, and regulated by metabolism. Autonomy here means active mediation of dependence, not self-sufficiency (Varela, Maturana, and Uribe 1974; Di Paolo 2005; Mossio and Bich 2017). Protocell research investigates the still unresolved transition to this coupling.

The distinction is nested and question-dependent. An organism supplies exo conditions for its cells and participates within ecological processes whose boundaries differ again. A household may be the relevant organisation for a transaction, yet part of a person's environment. No scale has final privilege: boundaries require evidence of integration, reproduced constraints, relevant exchanges, and temporal scope. Endo–exo is consequently a grammar of organisation and dependence, not another version of subject–object or mind–body dualism. Transformation of an exo never makes dependence irrelevant.

### 2.4 Physical Living and Historical Temporality

Physical time concerns durations, frequencies, phase, relaxation, irreversibility, and event order. Living time concerns internally organised metabolism, repair, development, and reproduction. Its endogenous character remains exo-conditioned through energy, nutrients, environmental cues, and the times of other beings (Pittendrigh 1993; Montévil and Mossio 2015). This account neither reduces time to a homogeneous coordinate nor makes it a projection of consciousness.

Physical, biological, ecological, social, and historical temporalities interact without becoming interchangeable. Clock-time measures durations, but does not establish whether a process has the phase relations, developmental windows, or renewal conditions it requires. Institutions can coordinate these temporalities or bring them into destructive conflict. Financial returns demanded sooner than soil restoration, bodily recovery, democratic deliberation, or infrastructure repair create material mismatches among forms of reproduction, not merely disagreements about preferences (Georgescu-Roegen 1971).

### 2.5 Emergence Scale and Explanatory Pluralism

Emergence names relatively stable organisations that require more than a description of isolated components. A molecular inventory does not explain a cell's membrane maintenance; a list of organisms does not explain nutrient cycling; neural events do not exhaust linguistic norms (Anderson 1972). No mysterious force or separate world is implied. Higher-level constraints organise lower-level processes rather than violating their causality: membranes regulate transport, habitats alter population dynamics, and legal rules redistribute access and risk.

Scale changes the effective boundary, variables, horizon, and kind of explanation. Degrees of freedom do not simply increase from particles to people. Organisation suppresses many microscopic possibilities while opening new collective capacities through bonds, cellular cycles, nervous systems, language, or institutions (Levin 1992). Explanatory pluralism therefore requires material continuity and mutual accountability. Social accounts cannot ignore throughput; biological accounts cannot dismiss meaning as causally illusory; physics need not contain a vocabulary of justice to remain valid within its scope.

Coordination of partial explanations is preferable to premature unification.

### 2.6 Consequences for Inquiry

Every inquiry should identify the relevant form or boundary, the energetic and material processes crossing it, retained states and rhythms, the constraints reproduced through activity, and the exo conditions enabling or disrupting continuation. These questions establish a common grammar while preserving domain-specific methods. Claims must distinguish established findings, demonstrated mechanisms, plausible historical reconstructions, and conceptual synthesis, especially at transitions between chemistry and life, organisms and ecosystems, or communication and language.

The normative consequence is admissibility rather than a derivation of values from nature. Facts do not determine goodness or justice, but a project cannot count as viable while systematically destroying collective continuation's material, ecological, and temporal conditions. Truth, goodness, beauty, and fairness remain distinct questions situated within those enabling conditions. The programme treats unresolved transitions as research problems and real constraints as conditions of possibility rather than destiny.

## 3 A STRATIFIED NATURAL HISTORY FROM RELATIONAL PHYSICS TO PROTOCELLULAR ORGANISATION

A natural history adequate to ecological realism must preserve material continuity and organisational novelty. Living systems remain dependent on physical interactions, chemical transformations, and thermodynamics, yet a cell actively renews the organisation that makes its states possible. Neither deduction from particles nor an inexplicable interruption of physics captures this difference. The question is how new couplings acquired sufficient stability to become historically consequential.

### 3.1 Relational Physics and Bound Forms

Quantum systems are characterised through symmetries, couplings, conservation laws, possible states, and interactions. In relational quantum mechanics, facts are realised relative to physical systems rather than forming a catalogue of absolute actual properties (Rovelli 1996, 2021). Acceptance of that interpretation is not required for the narrower warning against picturing individuality as perfect self-enclosure.

An electron's mass, charge, spin, and couplings condition its possible relations; they are not a metabolism or self-produced boundary. Its quantum state includes phase and spatial or momentum distributions alongside spin, without regulating its own continuing existence. Endo–exo language is thin here. Nuclei, atoms, and molecules have dynamically stable bound configurations with spectra, resonances, vibrational modes, and reaction pathways. Their "interior" is a structured relation of allowed interactions, not necessarily an enclosed surface.

Such stability is temporal: characteristic organisation persists while perturbations remain within tolerable ranges. It is not biological self-maintenance. Nevertheless, spectra, geometries, and affinities retain differences that constrain later processes and supply chemistry's material possibilities. Calling these pre-linguistic "texts" is explicitly metaphorical. They are neither messages nor semantic signs, but durable differences through which the past conditions subsequent interaction.

### 3.2 Planetary Gradients and the Opportunity for Chemistry

A rocky planet can sustain temperature, pressure, redox, acidity, concentration, illumination, and phase differences through atmosphere, water, mineral surfaces, internal heat, gravity, and stellar energy.

Gradients enable flows and chemical work only through suitable pathways and constraints. They supply neither purpose nor sufficient organisation: energy can dissipate without producing durable complexity. The question is which material arrangements make a gradient consequential for a particular process.

Mineral surfaces concentrate reactants and alter pathways; wet–dry cycles change concentration; fluid interfaces sustain electrochemical differences; radiation, volcanism, hydrothermal activity, and daily or seasonal cycles open and close reaction opportunities. Hot-spring and hydrothermal accounts are researched scenario families addressing concentration, activation, catalysis, compartments, energy coupling, polymers, and persistence, rather than established rival origin stories (Damer and Deamer 2020; Russell and Hall 1997).

Planetary chemistry offers a changing landscape of formation and failure. Structures disappear, cycles recur without retained history, reactions inhibit themselves, and some feedbacks enrich particular compounds. This heterogeneous exo field makes multiple constrained pathways possible without preselecting a living organisation. Contingency therefore enters before life as plural material possibilities, not as freedom from physical conditions.

### 3.3 Dissipative Chemistry Autocatalysis and Selective Compartments

Dissipative systems can maintain local order through throughput and entropy export. Flames, convection cells, and chemical oscillators demonstrate that order and dissipation are compatible, but do not by themselves reproduce the constraints needed for biological persistence (Prigogine and Stengers 1984). Recurrence and feedback must be distinguished from autonomy.

Collectively autocatalytic networks couple reactions catalysed by network products with the production of required materials from an available food set. Formal models make specified kinds of self-sustaining organisation testable (Hordijk, Steel, and Dittrich 2018). Yet autocatalysis may exhaust substrates, support parasites, depend on narrow laboratory conditions, or fail to couple products to compartment growth and division. Replication, metabolism, heredity, and membranes are insufficient separately; their coupling matters (Deamer 2024).

Membranes, pores, vesicles, and coacervates can concentrate reactants and selectively retain products. A compartment becomes more than a passive container when internal chemistry contributes to its growth, repair, permeability, or division. A constraint imposed on reactions then becomes a constraint maintained through them (Damer and Deamer 2020; Deamer 2024). Feedstocks, solvents, catalysts, and temperature ranges constitute exo conditions; selected internal transformations constitute a possible endo. Their boundary is an ongoing selective exchange. The first membrane is thus a candidate site for the co-emergence of inside, outside, and mediation rather than a container placed around already existing life.

### 3.4 Protocells and Organisational Closure

Protocell research investigates which couplings permit persistence, growth, division, heredity, and evolution. Synthetic vesicles are not literal reconstructions of Earth's first organisms. They test combinations of membranes, nutrient uptake, primitive metabolism, catalytic polymers, replication, and regulatory feedback (Deamer 2024). A membrane without sustaining chemistry is fragile; an unconfined network loses products; a replicating polymer need not reproduce a viable whole. Models of metabolic heredity similarly show that growth-supporting catalysis must contribute to broader throughput rather than merely accumulate one product (Nunes Palmeira et al. 2022).

A minimal strong endo would require a selective persisting boundary, far-from-equilibrium material and energy throughput, feedback maintaining both boundary and network, and some retention, variation, and transmission of organisation across growth or reproductive cycles. These are analytical requirements, not four known chronological steps. Couplings may have arisen partially and repeatedly: temporary closure without heredity, polymers without integrated metabolism, or selection among compartments before modern genes.

The empirical task is to establish which couplings suffice for particular degrees of persistence and evolvability under plausible geochemical conditions. Endogenous time becomes substantive when internal phases, cycles, and retained differences contribute to reconstituting the whole. A reaction merely has duration; a protocell candidate begins to have its own time

when recurrence supports its continuation. Such organisation remains exo-conditioned by gradients, feedstocks, milieu, and tolerable perturbations.

### 3.5 Continuity Novelty and Historical Contingency

The transition is materially continuous but organisationally novel. A system that renews its constraints requires variables of boundary, metabolism, memory, and temporal coordination, not merely a component list. This need not imply a single sharp historical instant separating non-life and life.

Borderline systems and populations may have persisted for long periods. Geological evidence, prebiotic chemistry, synthetic biology, thermodynamic models, and comparative biology must determine the historical possibilities; philosophical criteria organise that inquiry without settling it (Varela, Maturana, and Uribe 1974; Mossio and Bich 2017).

Nothing in a particle entails a cell, nothing in a cell entails an animal, and nothing in an animal entails language or politics. Earlier forms constrain and enable later ones without predetermining them. New couplings stabilise new organisations within inherited materials and time scales (Anderson 1972). This bounded openness connects natural history with living time: metabolism, repair, development, and reproduction transform physical durations into coordinated conditions of continuation, without becoming independent of physical and ecological processes.

## 4 LIVING TIME METABOLISM REPAIR DEVELOPMENT REPRODUCTION AND ECOLOGICAL CO-REPRODUCTION

Living organisation introduces a distinctive temporality without leaving physical time or thermodynamic irreversibility behind. An organism does more than endure: its retained structures and current activities contribute to future continuation. Endogenous time names this coordination of rhythms, memory, constraints, and developmental trajectories. It requires neither consciousness nor self-sufficiency.

Transport, metabolism, repair, growth, and division are partly organised from within, while depending on throughput, viable chemical conditions, other beings, and environmental regularities (Varela, Maturana, and Uribe 1974; Di Paolo 2005). Living time is organised dependence within physical and ecological time.

### 4.1 From Duration to Organised Temporality

A chemical period becomes biologically consequential when coordinated processes maintain the constraints through which they continue. In organisational closure, membranes, enzymes, transport, metabolism, and repair are differentiated but mutually sustaining: relatively stable constraints channel transformations that reconstitute those constraints (Montévil and Mossio 2015). The organisation persists through material change rather than apart from it.

Biological persistence is therefore often a viable trajectory rather than a fixed state. Bodies grow, replace components, heal, develop, and age while maintaining recognisable relations of regulation and transformation. Waddington's homeorhesis captures the stabilisation of a course of change (Waddington 1957). Endo is this organisation, not everything spatially inside a membrane; exo is the field it selectively engages. A boundary localises and organises dependence instead of abolishing it.

### 4.2 Metabolism and the Active Maintenance of Difference

Metabolism maintains differences between an organisation and its milieu through acquisition, transformation, export, concentration control, and selective inhibition. Organisms remain thermodynamically open to remain organisationally distinct. They do not suspend entropy production: the defining feature is the coupling of flows with constraints maintained through those flows.

Biological individuality consequently exceeds a silhouette. Membranes, tissues, immune interfaces, epithelial surfaces, circulation, and behaviour create nested boundaries whose relevance depends on the process and scale. Repair clarifies the difference between durability and active renewal. Organisms can detect damage, recruit resources, replace components, and restore viable relations, although these capacities are graded and finite (Di Paolo 2005; Mossio and Bich 2017). Ageing and death expose their limits.

Endogenous time includes phases of uptake and release, synthesis and degradation, activation and inhibition, activity and rest, growth and repair. Their sequence affects what can happen next. A fluctuation harmless at one scale may threaten persistence

at another. The living present is a historically formed condition of readiness, vulnerability, and response rather than merely a point on an external clock.

### 4.3 Rhythms Clocks and Minimal Anticipation

Circadian clocks can continue for a time under relatively constant conditions while being entrained by light, temperature, feeding, or social activity. They coordinate physiology, behaviour, and repair with planetary regularities (Pittendrigh 1993; Marcheva et al. 2013). Their endogenous generation does not imply independence from material supply or evolutionary history. A clock is a coupling mechanism, neither a passive imprint of daylight nor an autonomous metronome.

Phase coordination permits preparation for conditions not yet present. Plants, animals, and microbes can organise activity around probable recurrent conditions without requiring a mental representation of the future. Past cycles become materially retained capacities for anticipation. Circadian rhythms are only one instance: cellular, hormonal, respiratory, tidal, seasonal, developmental, and reproductive rhythms have different scales and plasticities. Their viable coordination is itself an achievement (Pittendrigh 1993; Helm et al. 2013).

Clock-time remains indispensable for measurement, yet a standard hour does not disclose whether flowering, gestation, migration, or repair has sufficient time and appropriate conditions. Phase relations, thresholds, lags, developmental windows, and recovery matter. Altered cues or resource timing can destroy a viable relation while both participating organisms remain present. Time is part of ecological organisation, not simply its background.

### 4.4 Development Reproduction and Lineage Time

Development is a sequenced process of growth, differentiation, regulation, and interaction, not the execution of a complete plan in an empty environment. Genetic causation operates within cells, metabolic conditions, parental provisions, microbial partnerships, habitats, and environmental signals (Gilbert and Epel 2015). The point is to situate genes, not deny their importance. Development transforms exo conditions into changing organisation while remaining open to contingencies.

Reproduction reconstitutes viable organisation through replacement, variation, and dependence rather than copying an abstract essence into identical matter. Lineages persist only if offspring encounter conditions permitting development and further reproduction (Gilbert and Epel 2015; Laland et al. 2015). Neither an instantaneous individual nor a timeless lineage type adequately captures this continuity.

Organisms are situated temporal achievements; lineages are contingent histories of their renewal.

Finitude belongs to living time. Ageing, death, turnover, and generational replacement participate in the field through which life continues. This provides no justification for avoidable human injury or inequality. It establishes that continuity depends on renewal and vulnerability, rather than absolute self-preservation.

### 4.5 Ecological Co-Reproduction No Organism Has Its Time Alone

Organisms depend on habitats, food, water, symbionts, competitors, predators, pathogens, and material cycles that other organisms continually modify. Plants change soil and atmosphere, microbes transform nutrient availability, and animals transport matter and construct habitats. Environmental conditions are both inherited and historically made through niche construction (Odling-Smee, Laland, and Feldman 2003; Laland et al. 2015).

Co-reproduction names the reciprocal production, constraint, and sometimes destruction of these conditions without making an ecosystem harmonious or organism-like. Phenology demonstrates its temporal form: flowering, migration, emergence, breeding, dormancy, and resource pulses link species and trophic levels. Climate-driven shifts can separate pollinators from flowers or breeding from food availability, affecting fitness and ecological processes (Forrest and Miller-Rushing 2010; Visser and Gienapp 2019). An organism's time remains its own organised achievement, yet becomes viable only through the times of others. Organisational closure therefore means mediation of dependency, not independence from it.

### 4.6 Consequences for Ecological Realism

Endogenous time is an explanatory property of organisation rather than private experience or an additional physical dimension. Exo conditions are constitutive: they enter the formation of rhythms and capacities, rather than merely acting on a completed interior. Analysis must remain scale-sensitive because a relation stabilising a cell may disrupt an organism, and an

organism's advantage may damage an ecosystem.

Living futures are open through development, variation, and interaction, but bounded by inherited forms, ecological dependencies, and finite renewal times. These principles lead from individual maintenance to the differentiated co-reproduction of ecosystems and planetary conditions without requiring a master clock or a planetary subject.

## 5 ECOLOGICAL CO-REPRODUCTION ECOSYSTEMS BIOSPHERE AND THE MANY TIMES OF LIFE

Ecological co-reproduction names the historically layered relations through which life's conditions are renewed, transformed, or damaged: feeding, decomposition, competition, facilitation, pollination, dispersal, symbiosis, disease, habitat formation, nutrient and water cycling, migration, succession, and disturbance (Levin 1992; Folke et al. 2010). Predation, parasitism, mortality, and collapse belong to this texture. No intention to reproduce a harmonious whole is assumed.

A forest soil, reef, wetland, or microbial mat is a relatively stabilised nexus of biological and geophysical transformations. For an organism these conditions are exo, yet other organisms partly produce them. Ecology makes this dependence visible while preserving the distinct and sometimes conflicting organisations participating in it.

### 5.1 Ecology as a Field of Relations

An ecosystem is not an aggregate of organisms inside a container. Its form is an evolving pattern of populations, resources, habitats, flows, and constraints that affects persistence and responses to disturbance. Relevant boundaries follow processes: nutrient cycling, breeding populations, migratory ranges, and chemical gradients need not coincide. Scale-dependent boundaries require material and temporal justification rather than arbitrary convention (Levin 1992).

Ecosystems contain feedbacks and stabilising relations but generally lack a cell's integrated organisational closure. Their participants have overlapping and conflicting modes of reproduction. Co-reproduction is therefore more precise than ecosystemic selfhood. Inquiry asks which relations are renewed, through whose activity, at which scale, and at what cost elsewhere. It must distinguish changes in species composition that retain some functions from losses of feedbacks and cycles on which many organisms depend. Stability is always the stability of particular relations over particular times.

### 5.2 Energy Matter and Ecological Form

Energy throughput and material circulation are inseparable but asymmetric. Usable energy continually enters through solar or geochemical gradients and is degraded through transformation; carbon, nitrogen, phosphorus, water, and other materials can be repeatedly mobilised, stored, and reused.

Material recycling does not remove the need for renewed usable energy (Georgescu-Roegen 1971).

Food webs capture only part of ecological organisation. Decomposers, fungi, microbes, pollinators, dispersers, soils, and habitat-forming species reproduce conditions beyond direct feeding. Microbial metabolisms mediate many planetary electron transfers and biogeochemical cycles (Falkowski, Fenchel, and DeLong 2008). Apparent background conditions such as oxygen, nutrient availability, or soil structure are accumulated outcomes of living and geophysical processes.

Functional claims identify causal contributions within a specified system and time, not roles in a timeless design. A predator, decomposer, or pollinator can alter conditions without implying a preordained optimum or universal benefit. Ecological form is distributed across pigments, membranes, roots, bodies, microbial communities, water channels, and habitats. These forms channel energy and material flows while requiring continuous renewal through them.

### 5.3 Ecological Time Cycles Lags Disturbance and Regeneration

Rapid microbial transformations, daily metabolism, seasonal reproduction, soil and forest development, and climatic or geological processes coexist. Their couplings and delays often define the ecological relation (Levin 1992; Gunderson and Holling 2002). Persistence does not require an unchanging state.

Resilience concerns the disturbances a system can absorb without losing organising relations, alongside the distinct question of return speed (Holling 1973).

Regeneration is a temporal relation, not a stock available on demand. Timber volume omits soil formation, dispersal, fungal

partnerships, water relations, and succession; fish biomass omits age structure, habitats, trophic interactions, and reproductive timing; chemical soil inputs omit biological structure and history. Extraction must be related to whether the relevant organisation has time and conditions to renew (Folke et al. 2010).

Fire, flood, drought, disease, storms, and migration can destroy relations or open new trajectories. No universal baseline determines recovery. Surviving organisms, legacies, landscape form, climate, and surrounding systems constrain subsequent possibilities. Lags and thresholds can make apparently modest changes difficult or impossible to reverse. Contingency is real, but every trajectory inherits a material history (Gunderson and Holling 2002; Folke et al. 2010).

### 5.4 Niche Construction and Ecological Inheritance

Organisms modify the conditions to which they and others respond. Beavers change hydrology, plants modify soils and microclimates, corals build habitat, and fungi and microbes transform nutrients. Such activity changes developmental and selective conditions rather than merely adapting to an imposed environment (Laland et al. 2015).

Its traces can outlast their makers. Burrows, nests, reefs, seed banks, soil structures, decomposed bodies, or altered nutrient cycles become ecological inheritances mediating past activity and future possibility (Odling-Smee, Laland, and Feldman 2003). This is neither environmental control nor necessary benefit: local modifications can expose their makers to new risks and undermine others.

Interacting trophic, mutualistic, and engineering dependencies can generate nonlinear community effects and extinction cascades (Yeakel et al. 2020).

Ecological memory is thus distributed in soils, waters, atmospheres, habitats, species composition, and ranges, as well as genes. It can support recovery or transmit degradation through fragmented habitats, depleted soils, lost pollinator relations, and changed fire regimes (Gunderson and Holling 2002). These legacies are altered possibilities rather than simply absent quantities.

### 5.5 Planetary Co-Production without a Superorganism

Life has transformed Earth's surface conditions rather than merely adapted to a finished planet. Photosynthesis, microbial metabolism, vegetation, marine organisms, and organic burial and release have shaped atmosphere, oceans, soils, and subsequent life (Falkowski, Fenchel, and DeLong 2008). This establishes a biosphere, not a single organism with unified purpose, perception, or reproductive closure.

Planetary feedbacks emerge from distributed interactions among life, atmosphere, hydrosphere, lithosphere, solar radiation, and the interior of Earth. They may stabilise or destabilise conditions for particular species. Endo–exo remains useful only when specified: planetary processes are open to solar and geological influences, orbital variation, and events beyond Earth, while biotic and abiotic processes co-constitute conditions internally.

The research question is which couplings sustain or erode habitability across scales. Neither a passive resource store nor an automatically self-healing planet provides an adequate image. Geological durability offers no guarantee for a particular civilisation. Habitability is a contingent historical achievement whose finite feedbacks and renewal processes can be overwhelmed or reorganised (IPCC 2023; IPBES 2019).

### 5.6 Consequences for Ecological Realism

Ecological explanation must follow relations that move matter and energy, reproduce constraints, form habitats, and coordinate rhythms. Such relations are measurable dependencies rather than merely ways of knowing. Co-reproduction explains relative order without a final equilibrium, evolutionary ladder, or unified planetary agent.

Time is also a condition of admissibility. Short-term output may consume soils, water, reproductive capacity, habitat complexity, or climatic regularity needed later, creating an ecological temporal debt. Recognising this does not derive politics from ecology; it establishes that destroying renewal times undermines viability (Georgescu-Roegen 1971; O'Neill et al. 2018). Endo–exo remains mediation among distinct but dependent forms, becoming more actively selective through animal sensing, movement, learning, and anticipation.

## 6 ANIMAL WORLDS SIGNIFICANCE MOVEMENT LEARNING AND PRACTICAL ANTICIPATION

Animals encounter differences as relevant to food, danger, shelter, mates, offspring, injury, and movement. Relevance arises through embodied capacities to sense, act, and remember within a shared material world (Thompson 2007; Di Paolo 2005). This is not an evolutionary ladder: plants, fungi, and microbes also regulate and sense. Animal organisation characteristically integrates mobility and sensing, often with nervous coordination, so movement alters perception and learned outcomes shape further action (Noë 2004; Di Paolo, Buhrmann, and Barandiaran 2017).

The animal's endo includes metabolism, bodily integrity, affect, perception, learned dispositions, and action coordination. Its exo is a field of affordances, resistance, signals, and other beings. Their relation is an active loop rather than exchange between two completed substances.

### 6.1 Umwelt and Species-Specific Relevance

Uexküll's Umwelt names the operational unity of a perceptual world, Merkwelt, and an effector world, Wirkwelt. What an animal discriminates is coupled to what it can do, while action changes subsequent discrimination (von Uexküll 1934/2010). This avoids both anthropomorphism and the image of organisms sealed in private worlds. Species encounter the same world through different scales, capacities, and regularities: ultraviolet patterns, chemical trails, vibrations, or echolocation may be differently consequential (Bueno-Guerra 2018).

A flower has physical properties independently of an encounter, yet becomes nourishment, prey location, or irrelevant background through relations with particular bodies and needs. Relevance belongs neither exclusively to the object nor to an inner projection. Experiments must therefore identify differences available to the organism, actions its body permits, and ecological and social conditions giving a response significance. Attention to species-specific organisation increases objectivity by correcting the assumption that human priorities supply a universal measure.

### 6.2 Perception as Active Sensorimotor Mediation

Eyes move, whiskers sweep, noses sample, ears orient, and bodies reposition to change what can be sensed. Movement is part of perception rather than only a response to it; active touch exemplifies sensing through control of the sensory apparatus (Prescott et al. 2011). An action changes incoming conditions, alters bodily coordination, and prepares another action.

Gibson's affordance names an action possibility in the relation between environmental form and organismic capacity (Gibson 1979). A branch can be a route, perch, obstruction, or unusable surface depending on the animal. Endo does not invent the world and exo does not inscribe it on a passive body. Sensorimotor action tests whether coordination succeeds within real constraints, without necessarily constructing a complete inner replica (Noë 2004; Di Paolo, Buhrmann, and Barandiaran 2017).

Neural descriptions explain integration, regulation, and learning but cannot alone determine a signal's practical meaning. That depends on the embodied organism's wider relation to consequences. Nervous systems extend sensorimotor mediation rather than replacing it (Thompson 2007).

### 6.3 Affective Orientation and Practical Significance

Animal worlds are valenced. Hunger, pain, fatigue, safety, attachment, arousal, fear, and play alter what solicits or interrupts action. These are neither moral judgments nor irrelevant internal disturbances.

They make bodily conditions consequential for environmental engagement (Thompson 2007).

This establishes minimal biological normativity: an action can maintain or restore a viable relation, or expose an organism to injury, exhaustion, predation, or reproductive failure. "Good for" an organism does not yet mean morally good (Di Paolo 2005; Mossio and Bich 2017). Material cues become signs when they orient action before direct encounter with what they indicate. Calls, scents, tracks, colours, and movements enter histories of coordination rather than functioning as disembodied propositions.

Significance therefore cannot be equated with physical difference alone or with a mind's arbitrary addition. A real difference matters through its consequences within organised life. Exo events alter endo processes, while bodily states change which environmental relations become available, threatening, or avoidable.

### 6.4 Learning Memory and the Temporal Deepening of Action

Learning retains past interactions as modified capacities for future perception and action, through neural, hormonal, motor, attentional, and social changes. It need not involve conscious recollection (Thompson 2007). Memory is the continuing availability of a relation in present organisation, also supported by paths, nests, caches, territories, seasonal cues, partners, and habitat structures. It is endo-based and exo-conditioned.

Anticipation ranges from rhythms and learned contingencies to action responsive to later needs or opportunities. Western scrub-jays cached food in places where they had learned it would later be unavailable, challenging accounts restricted to present motivation (Raby et al. 2007). Such findings do not establish human-like mental time travel in every animal. Mechanisms and scope vary and remain empirical questions.

The limited conclusion is that absent but practically relevant future conditions can shape present action. Animal time thus includes retained past, oriented movement, and preparation within bounded possibilities. Rapidly altered regularities, lost habitats, fragmented routes, and disrupted social learning can prevent these capacities from being enacted as before (Helm et al. 2013; Visser and Gienapp 2019).

### 6.5 Space Sociality and Shared Animal Worlds

Territories, home ranges, nests, migration routes, refuges, and hunting grounds are fields of access, risk, memory, and possibility. Near and far concern reachability or escape within available energy and time, alongside metric distance. Habitat fragmentation can therefore break routes, cues, seasonal sequences, and relationships rather than simply reduce area.

Social worlds are partly co-regulated through care, vigilance, play, coordinated movement, calls, grooming, competition, alliances, and imitation. Young animals inherit practices through others as well as through genetic development (De Jaegher and Di Paolo 2007). Sophisticated communication and social transmission do not automatically constitute an open public system of concepts, reasons, and institutions. They nevertheless establish continuity: meaning can be shared through bodies, places, rhythms, and interaction before becoming explicitly symbolised and normatively contested in language.

### 6.6 Consequences for Ecological Realism

Significance precedes language without collapsing into physical causation. Perception and action belong to an organised mediation of affect, movement, memory, and environmental form. Anticipation expresses bounded openness: possibilities are neither predetermined nor unlimited, but structured by bodies, histories, social relations, habitats, and ecological rhythms.

Human distinctiveness must be investigated from these continuities while preserving qualitative change. Language and institutions emerge within embodied and ecological life, yet create a public symbolic and normative field that cannot be described simply by extending animal capacities quantitatively. Their freedom remains a transformation of dependence rather than an escape from it.

## 7 LANGUAGE LOGICAL ARTICULATION ASSOCIATIVE MEANING AND SYMBOLIC REORGANISATION

Human language develops from animal attention, signalling, learning, and social coordination, but is not reducible to any one capacity or an inevitable evolutionary culmination. Signs become publicly reusable and recursively interpretable, coordinating relations with absent, possible, remembered, and imagined realities (Tomasello 2008; Clark 1996). Speech, gesture, signing, and inscription remain bodily and technical events, while their relative autonomy permits denial, metaphor, fictional narration, and criticism of rules. Ecological realism investigates this autonomy together with its dependence on material and social practice.

The texture of life thereby becomes capable of articulating its conditions explicitly. Science, art, law, religion, collective memory, technical cooperation, and political conflict become possible alongside abstraction, domination, and ecological forgetting. Symbolic means that signs can themselves be cited, interpreted, corrected, and made answerable before others, rather than that they occupy an immaterial realm.

### 7.1 From Animal Significance to Shared Symbolic Reference

Animal life already contains signs and shared practices. The distinctive transformation is shared symbolic reference:

participants make something jointly available as what they are speaking about, rather than merely affecting another's behaviour (Tomasello 2008). Shared attention and collaborative intentionality help establish this field of common reference (Tomasello et al. 2005). The evolutionary sequence remains contested, and no single trait explains language.

Displacement extends reference to yesterday's animal, a distant river, an obligation, a number, an ancestor, fiction, or a hypothetical event. It enables collective work and anticipation beyond immediate perception without making language unreal. Absent conditions become actionable in the present (Clark 1996).

Reference is learned through pointing, showing, asking, naming, recounting, working, playing, and caring. Children acquire neither a complete inner dictionary awaiting attachment to objects nor a code independent of context. They learn how signs direct attention, how others respond, and how use persists or changes across situations. Individual linguistic capacities are therefore endogenous yet conditioned by an already social, material, and historical field.

### 7.2 Language as Embodied Multimodal and Public

Voice, gaze, timing, posture, gesture, hands, face, spatial movement, writing tools, and surfaces participate in communication. No sign is reducible to one vehicle, yet none exists without material mediation. Iconicity connects form and meaning in both spoken and signed languages alongside convention and arbitrariness (Perniss, Thompson, and Vigliocco 2010).

Meaning is not a substance contained in sound or marks. It is stabilised through practices in which participants learn what differences signs make and how uses can be corrected (Clark 1996). Publicness permits re-encounter, recognition, teaching, and contestation. It requires partial intelligibility rather than consensus: communities dispute meanings and inherit unequal authority to define them.

The field of language is exosomatic relative to a child, preceding and conditioning its development, while remaining constantly renewed by embodied speakers and signers. It is neither a private consciousness

nor an external system capable of operating without living practice. Bodies and communal histories shape its rhythms through care, work, play, and shared attention.

### 7.3 Logical Articulation Concepts Negation Inference and Public Reasons

Language permits distinctions to be maintained, related, and revised: this and not that, same and different, possible and impossible, if and then. It enables assertion, denial, requests for reasons, comparison with evidence, and inference beyond direct perception (Clark 1996). Ordinary language is not a formal calculus, but can distinguish promises from reports, explanations from excuses, and contradictions from differences of emphasis.

Counterfactuals make alternative dams, harvests, treaties, or educational arrangements collectively discussable. Logical articulation thus enlarges anticipation and public accountability. Claims can be challenged by others, records, calculations, experiments, and the resistance of the world. Truth is a normative achievement within historically situated practices answerable to reality, not mere agreement or private certainty.

Descriptions such as "timber," "resource," "human capital," or "wealth" select aspects of forests, rivers, persons, and debts. They do not cancel the processes and dependencies enabling continuation. Logical power can reveal these conditions or systematically abstract from them. An ecological account must therefore retain both the social formation of concepts and their responsibility to real consequences.

### 7.4 Associative–Semantic Opening Metaphor Narrative and Plural Meaning

Words also evoke histories, images, affect, analogy, rhythm, memory, and values. A river can be a watercourse, boundary, food source, sacred site, childhood place, danger, or temporal metaphor. Relevance varies with practice and history; meanings cannot simply be reduced to one another (Lakoff and Johnson 1980; Ricoeur 1984).

This openness supports creativity, interpretation, and renewal. Metaphor can disclose a relation before its conceptual stabilisation; narrative connects events through inheritance, responsibility, loss, and possibility; poetry can attune perception to differences missed by instrumental vocabularies. Logical and associative dimensions are therefore neither separate faculties nor rivals. Scientific concepts have semantic histories; poems can make distinctions and alter action. Conceptual clarity requires interpretive richness, while association remains answerable to criticism.

This double character enables freedom from one-to-one stimulus responses. Yet imagined alternatives arise through bodies, languages, landscapes, techniques, and histories, and their effects encounter material consequences. Linguistic possibility does not remove the need to eat, breathe, care, work, and live within finite regenerative capacities.

### 7.5 Language Time and the Transformation of Endo–Exo Relations

Language makes past, future, and possibility explicitly shareable. Communities recount distant events, preserve obligations, dispute histories, compare alternatives, and address generations not yet born. The future becomes a field of deliberation, promise, warning, imagination, and struggle (Ricoeur 1984; Orianne and Eustache 2023).

Language itself is inherited and transformed through conflicts, migrations, institutions, ecological settings, and labour. Its reflexive memory lets signs refer to previous signs and revise their interpretation. This extends, rather than inaugurates, material, biological, ecological, and animal retention. Symbolic space likewise enables mapping, borders, routes, distant coordination, and wider care, while permitting remote appropriation and concealed costs.

The human endo includes internalised concepts, memories, affects, and habits; its social–symbolic exo includes shared signs, stories, rituals, tools, and institutions. Neither replaces bodily life. Their causal efficacy remains conditioned by energy, materials, ecosystems, and renewal time. Expanded symbolic horizons consequently reorganise dependence rather than overcoming it.

### 7.6 Relative Autonomy Ecological Dependence and Critique

Because signs can be recombined and criticised, people can contest categories, name previously normalised injuries, expose neglected dependencies, and imagine new institutions. Critique is a real capacity emerging within ecological life, not an illusion to be explained away.

The same autonomy allows evaluation to detach from consequences. Money, titles, administrative categories, indicators, and ideological narratives can mobilise action while obscuring soils, care, bodies, and future renewal. Abstraction is indispensable to science, law, and cooperation; the issue is whether it remains admissible within the life it organises (Bowker and Star 1999; Polanyi 1944).

Truth, goodness, beauty, and fairness cannot be deduced from biology, yet practices claiming them lose durable credibility if they destroy common continuation. Language's powers of reasoning and imagination therefore carry responsibility for a more adequate relation between the symbolic world and its living conditions. Technics and institutions amplify this possibility and its dangers through forms that retain meaning beyond individual encounters.

## 8 EXOSOMATIC MEMORY TECHNICS AND INSTITUTIONS THE EXTERNALISATION OF COMMON REPRODUCTION

Language acquires historical durability through material forms retaining signs, skills, obligations, and practical arrangements. Paths, tools, marks, calendars, maps, archives, laws, and databases make absent relations consequential in present action (Hutchins 1995). Exosomatic memory names socially maintained material arrangements that retain and transform differences beyond interruption, distance, and particular persons' lives. A page does not remember alone, and a community is not one remembering organism; interpretation and practice reactivate retained forms.

Externalisation transforms common reproduction: the renewal, repair, and revision of conditions people share but cannot each reproduce alone. Language, skills, care, food, water, dwellings, tools, infrastructure, habitats, cooperation, and decision institutions belong to it. "Common" means interdependence, not necessary harmony or common ownership. These conditions are often unequally controlled and contested. The question is how exosomatic organisation expands collective capacities without undermining its own conditions.

### 8.1 Exosomatic Does Not Mean Disembodied

Words, tools, records, and institutions precede individuals and constrain their possibilities, yet exist only through bodies that use, teach, repair, contest, and transmit them. Archives require media, energy, maintenance, access rules, and readers; law requires enactment, interpretation, enforcement, and recognition. Exosomatic forms are organised material mediations, neither an immaterial superstructure nor inert objects.

Remembering also involves selection, reactivation, interpretation, and forgetting. Maps, accounts, and monuments retain some relations while excluding others. Individual recollection, collaborative memory, and socially organised remembering should be distinguished rather than attributed to a collective consciousness (Orianne and Eustache 2023).

Bodies learn with things instead of projecting an already complete cognition outward. Instruments, pots, drawings, keyboards, and workspaces shape gesture, attention, timing, correction, and cooperation.

Inherited constraints orient practice; practice reproduces or changes those constraints; the altered field conditions future activity. Exosomatic memory is therefore retained form renewed through social endo–exo relations.

### 8.2 Technics as Material Mediation

A technical object stabilises possibilities of action through composition, dimensions, resistance, interfaces, and connections. Knives, looms, microscopes, nets, pumps, and programs organise bodies, materials, skills, sequences, and outcomes. They cannot be reduced to makers' intentions. Neither instrumentalism, which imagines neutral means controlled by sovereign users, nor determinism, which makes technology dictate society, captures this mediation.

Technical forms arise within needs, conflicts, materials, and institutions, then redistribute skills, attention, access, risk, and authority. Material-engagement approaches investigate this reciprocal formation of brain, body, artefact, and practice (Malafouris 2019). Ecological realism further asks what permits their reproduction: every device has supply chains, energy needs, maintenance, wear, extraction and waste effects, and a distribution of competence.

Differences between a locally repairable tool and a satellite network concern actual dependencies rather than an a priori preference. Apparent autonomy can conceal fragile or destructive exo conditions (Larkin 2013). Bodies become trained through technical affordances while skills become sedimented in tools and routines. Coupling transforms embodiment without abolishing distinctions among persons, objects, and institutions (Di Paolo, Buhrmann, and Barandiaran 2017).

### 8.3 External Memory and the Expansion of Common Time

Spatial arrangements, crafted objects, bodily techniques, images, and oral forms already retain practical differences; writing, numbering, maps, archives, clocks, and digital records extend this capacity.

Archaeological work treats persistent spaces, culturally shaped bodies, and material symbols as epistemic niche construction supporting public coordination over time (d'Errico, Meneganzin, and Colagè 2026).

The novelty exceeds storage. Records can sustain obligations after speakers depart, connect growing seasons, coordinate journeys across generations, and allow scientific claims to be checked by absent witnesses. The shared temporal field expands to include projected outcomes, schedules, future dangers, and commitments outlasting present participants (Hutchins 1995; Clark 1996).

Cumulative culture depends on such transmission without guaranteeing progress. In a controlled experiment, access to process-relevant social information enabled groups to produce more complex virtual artefacts than isolated individuals (Derex and Boyd 2015). The result supports the efficacy of transmissible knowledge and organisation, not inevitable wisdom or ecological adequacy. Knowledge can be lost or monopolised, and power can increase while repair time diminishes.

Durability itself requires care. Documents depend on media, languages, custodians, and interpretive practices; databases on hardware, power, formats, access, and institutions. Failure or commercial closure can erase practical availability. External memory redistributes the material labour of remembering rather than abolishing finitude (Larkin 2013).

### 8.4 Institutions as Retained Relations

Institutions stabilise common activity through roles, permissions, procedures, expectations, records, sites, and material supports. Schools, courts, cooperatives, municipalities, unions, laboratories, markets, and watershed councils organise different forms of participation, authority, responsibility, and continuity (Polanyi 1944; Ostrom 2009). Their identity resides in reproduced practice rather than a single building or charter.

An institution has a qualified endo through admission, decision, records, dispute resolution, competence, and rule revision. It is not biologically self-producing. Labour, energy, materials, ecological settings, law, trust, power, and knowledge are conditions of its operation; failure can turn it into an empty name before formal dissolution.

Persistence requires continual enactment, interpretation, cleaning, teaching, repair, legitimacy, and adaptation. Official success may conceal unequal care and ecological burdens. Inquiry must ask how an institution persists, for whom, and at whose expense (Larkin 2013). Ostrom's social–ecological framework connects resource systems, units, users, and governance as interacting subsystems (Ostrom 2009). Ecological realism adds explicit attention to retained forms and temporal horizons: rules must register feedback, enable repair, and allocate responsibility across the times of the processes governed.

### 8.5 Infrastructure Standards and the Material Conditions of Coordination

Roads, water systems, ports, grids, communication networks, schools, housing, hospitals, and platforms organise access, pace, visibility, dependence, and vulnerability. They create pathways for matter, energy, people, signs, and decisions and make repeated coordination into an inherited environment (Larkin 2013).

Standards likewise stabilise comparison through units, time zones, projections, data formats, protocols, and legal categories. They enable cooperation while selecting participants and deciding which differences count. A standard may clarify a relation or obscure it through an inappropriate scale or horizon (Bowker and Star 1999).

Digital information exemplifies material dependence. Symbolic content requires minerals, fabrication, electricity, cooling, networks, skilled maintenance, security, and disposal or reuse. Apparent instantaneousness rests on extended processes. Ecological analysis must follow their labour, throughput, effects, and repair times. A platform's internal boundary may omit users, attention, electricity, legal systems, and ecosystems; these exclusions do not make such conditions irrelevant. A city, watershed, or energy system may be the appropriate boundary for another inquiry. No analytical boundary confers immunity from excluded dependencies.

### 8.6 Power Abstraction and Ecological Forgetting

Control of archives, classifications, standards, platforms, routes, and valid evidence shapes collective memory and possible futures. Power often operates through ordinary forms: database defaults, timetables, property registers, procurement rules, and performance metrics render some activities more visible and rewardable than others (Bowker and Star 1999; Larkin 2013).

Counting, modelling, law, money, and measurement can reveal inequalities, trace pollution, and support criticism. They become ecologically dangerous when their selectivity is forgotten. Prices may omit soil renewal, unpaid care, distant damage, and future hazards; output indicators can hide maintenance and resilience; archives may exclude those bearing official decisions' costs (Bowker and Star 1999; Georgescu-Roegen 1971).

Excluded costs persist as exhausted bodies, degraded habitats, failed infrastructure, conflict, and foreclosed possibilities. Ecological forgetting is an organised failure of relation, open to investigation: which feedbacks are blocked, whose time is shortened, whose labour or habitat disappears, and which repairs become impossible?

Admissibility requires more than internal efficiency, legality, novelty, or familiarity. Exosomatic forms must receive material and ecological feedback and permit repair, deliberation, and revision. This is no single algorithm for normative judgment, but a condition of its durable practical relevance.

### 8.7 A Research Programme for Exosomatic Worlds

Archaeology, anthropology, cognitive science, history, design, political economy, ecology, engineering, and democratic theory can coordinate without adopting one final vocabulary. Inquiry should identify what is retained or actionable; the material carriers, flows, and maintenance involved; the bodies and institutions reproducing the arrangement; exclusions and subordination; temporal horizons opened or closed; and channels admitting ecological evidence and critique.

These questions support empirical studies of irrigation knowledge embedded in channels and schedules, hospital information systems distributing care, platform standards hiding labour or impacts, indigenous practices transmitting obligations, and archives enabling or restricting democratic revision. Each case requires specified forms, processes, scales, and endo–exo relations.

Human freedom consists in historically achieved capacities to reorganise dependence knowingly, collectively, and contestably. Memory, technics, and institutions make these capacities durable, potentially extending care across distance and generations. They also concentrate power and accelerate extraction. Their future is neither technologically inevitable nor unconstrained choice, but a contested field of bounded possibilities within the texture of life.

## 9 CONCLUSION ECOLOGICAL REALISM AND THE POLITICS OF COMMON REPRODUCTION

Ecological realism connects physical, biological, ecological, animal, symbolic, technical, and institutional realities while preserving their differences. Every energy process has a form, and every form exists through formation, maintenance, repair, and transformation. This is a research discipline rather than a reductive law: identify retained differences, the processes renewing them, the conditions required, and the consequences for other life.

The resulting history is a vulnerable texture rather than a ladder. Bound matter enables chemistry; selected chemical couplings open possibilities of living organisation; organisms and ecosystems acquire differentiated temporalities; animals develop practical significance and anticipation; language makes absence and possibility publicly articulable; technics and institutions externalise common reproduction. Each transition introduces novelty without escaping earlier material conditions.

### 9.1 Claims and Limits of the Programme

The four commitments are real material and temporal conditions, the causal efficacy of organisation, bounded historical contingency, and normativity dependent on life without being reducible to it. Prices, names, denial, and agreements cannot repeal ecological dependencies. Boundaries, memories, meanings, and institutions nevertheless change the processes possible within them.

The programme does not solve quantum measurement, life's origins, language emergence, or ecological democracy. Nor does it attribute the same kind of interior to particles, cells, watersheds, communities, and states. Different problems require different evidential standards. Question-dependent boundaries remain constrained by causal organisation, rather than arbitrary. Scale changes the effective variables and horizons; inquiry must articulate form, process, function, and state without assuming a final view outside all relations (Levin 1992).

### 9.2 Time Dependence and Bounded Openness

Living time organises metabolism, repair, development, memory, and reproduction while remaining supplied and entrained through energy, matter, habitat, seasons, and other beings. Ecological regeneration, succession, migration, decomposition, disturbance, and recovery cannot be compressed into one organism's clock (Pittendrigh 1993; Montévil and Mossio 2015).

Language and exosomatic memory extend common time through critique, records, standards, infrastructures, and intergenerational coordination. Their short internal clocks can also conflict with bodily recovery, care, learning, repair, and regeneration (Hutchins 1995; Larkin 2013). Bounded openness means existing skills, damaged habitats, infrastructures, and obligations condition future action while remaining open to reinterpretation and transformation. Freedom is exercised within dependency through the capacity to recognise and reorganise it, avoiding both fatalism and voluntarism.

### 9.3 Political Economy as an Ecological Question

Money, property, firms, markets, states, and financial instruments organise claims on labour, attention, techniques, energy, materials, land, and sinks. Symbolically constituted forms have real effects, but their prices represent only selected relations (Polanyi 1944; Georgescu-Roegen 1971). Political economy consequently belongs at the programme's centre rather than as a later application.

Capitalisation converts anticipated revenues into present value, enabling investment and innovation while potentially presenting the future as monetisable claims and relegating bodily, infrastructural, and ecological renewal to delayed costs. Calculation remains necessary; the issue is what it excludes and for how long. Common reproduction must therefore precede exchange as the organising question.

Property should be examined as a custodial power carrying duties to maintain, repair, avoid destruction, and transmit conditions. Production must be judged against throughput, regeneration, and care rather than output value alone. Voluntary contracts do not establish fairness where background conditions radically distribute vulnerability, knowledge, and burdens.

Admissibility asks whether inputs can be renewed, residues absorbed or repaired without displaced irreversible harm, maintainers and institutions reproduced, and corrective feedback received before damage becomes irreparable. Profit, legality, narrow efficiency, and promised compensation are insufficient. Irreplaceable conditions of life require no-exception zones rather than unlimited trade-offs.

The aim is an organised path towards civilisational and biospheric continuity instead of civilisational and biospheric collapse (O'Neill et al. 2018; IPCC 2023; IPBES 2019).

### 9.4 Commoning Reproduction and Democratic Form

The political task is to reconstruct democratic capacity around shared conditions of life, connecting local knowledge with wider coordination, evidence with experience, and present needs with future obligations. Neither an all-powerful state nor small-scale self-sufficiency follows. Institutions must make boundaries, evidence, risks, time use, and excluded relations publicly contestable (Ostrom 2009; Folke et al. 2010).

Four irreducible orientations guide judgment. The true concerns accountability to reality and evidence; the good concerns reciprocal agency and responsible collective action; the beautiful concerns qualitative fittingness, care, and an inhabitable world beyond inputs; the fair concerns access, burdens, reciprocity, power, and participation. They are related dimensions of judgment, not mechanically separable boxes.

Bodies require recovery, children care and learning, institutions deliberation and upkeep, infrastructure inspection and repair, and ecosystems regeneration. Protecting these times distinguishes transformation that renews capacity from acceleration that consumes future possibilities. Circulation cannot indefinitely outrun the renewal of the forms enabling it (Folke et al. 2010; O'Neill et al. 2018).

### 9.5 A Programme of Inquiry and Practice

Empirical work investigates emerging and breaking forms, organised dependencies, temporal conflicts, institutional memory, power, and effective ecological feedback. Philosophy clarifies their categories without reduction. Political practice concerns property, accounting, infrastructure, and democratic arrangements supporting common reproduction.

Correction is essential. Laboratory findings, mathematical models, field studies, archaeological reconstructions, archives, practical knowledge, and normative arguments are distinct contributions rather than interchangeable proofs. Excluded voices matter because official abstractions can miss dependencies first registered by those bearing their costs, not because all claims are equally true.

Human beings are a late and vulnerable strand of an older texture, with distinctive powers to destroy or repair its relations. Many common futures remain possible, but each must be made, maintained, and transmitted within the living world that makes any future possible.

## Appendix A The 4 × 4 × 4 Grammar of Ecological Realism

This research device combines four domains of organisation, four analytic registers, and four normative orientations. Its sixty-four intersections are places for questions, not separate substances, predetermined answers, or policy scores. It guards against reducing organisation to components, reifying interpretive categories, and detaching institutions from their conditions of continuation.

### A.1 Four Domains of Organisation

| Domain | Concern and typical forms | Caution |
|---|---|---|
| Physical–material | Bound forms, gradients, fields, particles, molecules, phase relations, reactions, and irreversible transformation | Form alone establishes neither biological autonomy nor semantic meaning. |
| Living–organismic | Self-maintenance and endogenous time through membranes, metabolism, repair, development, reproduction, and heredity | Organisms remain dependent on environments and lineages. |

| | | |
|---|---|---|
| Ecological | Co-reproduction through food webs, habitats, microbiomes, hydrology, nutrient cycles, disturbance, and regeneration | Ecosystems and biosphere are not one unified organism. |
| Symbolic–institutional | Public meaning, exosomatic memory, technics, rules, language, archives, infrastructure, law, money, organisations, and states | Symbols and institutions remain embodied and materially, ecologically, and temporally dependent. |

The domains are coupled rather than sealed layers. Soil can simultaneously involve chemical transformation, metabolic conditions, ecological relations, and institutional regulation. Distinction preserves domain-specific evidence while making their couplings explicit.

### A.2 Form Process Function and State

| Register | Guiding question and status | Error to avoid |
|---|---|---|
| Form | Which relatively stable constraint, boundary, relation, or pattern affects possibilities? Ontological and scale-sensitive. | Equating form with timeless substance or appearance. |
| Process | What transforms, flows, dissipates, reproduces, or breaks down through time? Ontological and temporally specified. | Imagining formless motion or automatic progress. |
| Function | What contribution does a component or relation make to a specified organisation's continuation or transformation?<br>Relational and explanatory; requires evidence. | Assuming intention, benefit, or moral approval. |
| State | What configuration obtains at a stated time, scale, and observational frame? Situated and epistemic, identified through measurement and models. | Treating a measured configuration as the whole process. |

Form and process identify inseparable poles of reality; function and state specify how inquiry situates it. Functions are not properties of isolated objects, and states are not views from nowhere. A membrane can be a cellular form, a process of lipid renewal, a metabolic functional constraint, and a transport model's state variable. These descriptions require articulation rather than substitution.

### A.3 Four Normative Orientations

| Orientation and classical site | Question | Ecological-realist requirement |
|---|---|---|
| True — Schole | What is the case, and what evidence permits correction? | Claims answer to real processes and consequences. |
| Good — Polis | Which common purposes, responsibilities, and forms of mutual agency are involved? | Collective purposes preserve conditions of continuation. |
| Beautiful — Oikos | What supports fittingness, qualitative flourishing, care, and inhabitable relations? | The world exceeds a stock of abstract inputs. |

| | | |
|---|---|---|
| Fair — Agora | How are access, burden, reciprocity, power, and participation distributed? | Costs and capacities are not displaced onto vulnerable, distant, or unborn others. |

This mapping is heuristic rather than a division into social sectors. A municipal heating study can examine physical process and truth in energy conversion; ecological state and beauty in air and habitat; institutional form and fairness in tariffs; or organismic function and goodness in thermal health and care. Domain × register × orientation displays coexistence without collapsing questions into one metric.

### A.4 Use and Limits

Specify the domain and register, explain provisional exclusions, state normative orientations when informing decisions, and test whether boundaries hide exo dependencies, longer times, or unequal burdens. Repeat as findings change the inquiry. Success means revealing a missing relation rather than filling every cell.

## Appendix B Endo–Exo Research Protocol and the Admissibility Test

This protocol translates the grammar into investigation of organisms, infrastructures, institutions, production systems, and policies. It guards against equating internal performance with viability rather than imposing a universal checklist.

### B.1 The IN → TRANSFORM → OUT → END Sequence

| Moment | Questions and necessary observations | Blind spot |
|---|---|---|
| IN | What enters, from where, and under what conditions? Identify energy, materials, organisms, labour, information, finance, permissions, land, and prior infrastructure. | Assuming inputs are free or indefinitely renewable. |
| **Moment** | **Questions and necessary observations** | **Blind spot** |
| TRANSFORM | Which constraints, operations, pathways, skills, procedures, labour divisions, metrics, rules, and maintenance organise transformation? | Treating activity as a black box or equating it with its stated purpose. |
| OUT | What leaves, for whom, and with which effects? Include goods, services, emissions, waste, data, obligations, risks, changed habitats, and capacities. | Counting valued outputs while externalising consequences. |
| END | What remains after transformation or closure? Identify residues, debts, restoration and care needs, decommissioning, learning, lost or inherited capacities, and ecological legacies. | Assuming a project's or transaction's end terminates its effects. |

END follows consequences across changes of form, boundaries, and generations. Delayed pollution, exhausted maintainers, lost skills, damaged ecosystems, unpayable debts, and inherited benefits remain part of the inquiry.

### B.2 Four Ledgers and Five Clocks

| Ledger | What it records | Question kept visible |
|---|---|---|
| Financial | Flows, claims, revenues, debts, ownership, budgets | Who commands resources and which obligations are recognised? |

| | | |
|---|---|---|
| Energy–material | Energy quality, throughput, stocks, dependencies, maintenance, waste | Which physical work and transformations enable activity? |
| Ecological | Sources, sinks, biodiversity, habitats, water, soil, climate, regeneration | Which living and geophysical conditions are altered or renewed? |
| Time | Durations, rhythms, care, learning, maintenance, repair, regeneration, inheritance | Whose time is used, what can renew, and which futures are foreclosed? |

These ledgers cannot automatically be added together. Financial gains do not by themselves cancel ecological losses, and technical benefits do not establish adequate repair time. The temporal ledger distinguishes five interacting clocks:

1. Pulse time comprises daily bodily and operational rhythms of work, care, transport, sleep, and attention.
2. Liquidity time comprises payment schedules, credit, debt service, and short financial pressures.
3. Capacity time concerns depreciation, upkeep, skill formation, learning, and technical durability.
4. Ecological-flow time includes seasons, water cycles, reproduction, harvest, decomposition, and regeneration.
5. Inheritance time includes long-lived infrastructure, pollution, biodiversity loss, climate commitments, cultural memory, and future generations' action-space.

Perfect synchronisation is not the criterion. The question is whether a short clock destroys the conditions enabling longer clocks to continue.

### B.3 The Admissibility Test

Provisional admissibility requires reasoned answers to six questions:

1. Are inputs available without pushing dependent systems beyond viable ranges?
2. Do transformations renew or erode the skills, bodies, infrastructure, habitats, and institutions they require?
3. Can outputs and residues be absorbed, reused, repaired, or governed without displaced irreversible harm?
4. Are maintenance, care, and restoration provided with resources and authority rather than assumed as unpaid background?
5. Can affected people and ecological feedback require revision before damage becomes unrecoverable?
6. Does the horizon include inheritances of those absent from present bargaining?

The test preserves conditions within which political disagreement remains possible rather than settling it. Conditions that cannot be restored through later compensation or substitution constitute no-exception zones: boundaries to action rather than ordinary trade-offs.

## Appendix C Evidence Discipline and Glossary

### C.1 Evidence Discipline across Levels

Bridges among disciplines require distinctions among findings, mechanisms, reconstructions, concepts, and judgments. Their warrants and limits differ.

| Claim | Warrant and appropriate language | Limit |
|---|---|---|

| | | |
|---|---|---|
| Direct empirical finding | Observation, experiment, measurement, reproducible analysis under stated conditions; "finds," "measures," "demonstrates in this system" | Does not alone establish a universal law or full philosophical interpretation. |
| Model-based mechanism | Explicit assumptions, mathematical or computational analysis, robustness, data comparison; "shows under these assumptions," "identifies a possible mechanism" | Does not establish that a mechanism occurred historically in every relevant case. |
| Comparative or historical reconstruction | Convergent traces, records, material evidence, contextual interpretation; "supports," "makes plausible," "is consistent with" | Does not yield deductive certainty about inaccessible events. |
| Conceptual synthesis | Clear definitions, coherence with established findings, explanatory fruitfulness; "proposes," "articulates," "clarifies" | Elegance does not constitute direct empirical confirmation. |
| **Claim** | **Warrant and appropriate language** | **Limit** |
| Normative-political proposal | Public reasons, consequences, democratic contestation, affected parties; "argues," "calls for," "should be assessed by" | Neither value-free nor mechanically derived from nature. |

This discipline is critical at transitions from chemistry to life, organismic organisation to ecology, animal significance to language, and coordination to legitimacy. Molecular models are not social theories, interpretations are not physical mechanisms, and ecological limits are not complete moral theories.

### C.2 Glossary of Core Terms

**Admissibility.** Compatibility with common continuation's material, ecological, and temporal conditions; a viability requirement rather than one moral value.

**Boundary.** A relatively stable distinction organising a process; physical, biological, technical, institutional, or analytical, with adequacy determined by question and scale.

**Common reproduction.** Shared renewal, repair, and revision of care, knowledge, infrastructure, habitats, democratic capacities, and other conditions no person can reproduce alone.

**Constraint.** A relatively stable form channelling processes, enabling some transformations while excluding or delaying others.

**Endo.** Organised transformations sustaining relative identity and states and, in stronger cases, reproducing their own conditions.

**Endogenous yet exo-conditioned time.** Time organised through living or social rhythms, memory, repair, and reproduction while remaining dependent on external matter, energy, regularities, and systems.

**Exo.** Conditions, gradients, flows, other systems, and historical circumstances enabling a process; not a wholly alien outside.

**Exosomatic memory.** Socially maintained material forms retaining consequential differences beyond particular individuals' duration or memory.

**Form.** A relatively enduring constraint or pattern affecting possible trajectories, rather than only appearance or timeless substance.

**Function.** An evidenced contribution to a specified organisation's continuation or transformation, without necessary intention or moral worth.

**Information.** Consequential difference retained in form; semantic information involves a further level of public symbolic interpretation and revision.

**Process.** Transformation through time, including movement, transfer, reaction, growth, repair, reproduction, learning, labour, exchange, degradation, and regeneration.

**State.** A configuration identified at a specified time, scale, and observational frame; necessary but never exhaustive of process.

**Texture of life.** The historically woven, differentiated, vulnerable field of physical, biological, ecological, animal, symbolic, technical, and institutional relations through which life is remade.

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