Toward an onto-dynamic structural realism

Abstract: In this paper, we defend a theory of structure that we term onto-dynamic structural realism. The theory rests on four core assumptions: the Galilean assumption (A1), the Noetherian assumption (A2), the Banach-Tarski-Bueno assumption (A3), and the Prigoginean assumption (A4). The latter provides a principled Prigoginean extension to ontic structural realism by incorporating insights from non-equilibrium thermodynamics. Whereas standard versions of ontic structural realism typically rely on fundamental physics and therefore say relatively little about dissipative structures, far-from-equilibrium dynamics, and the emergence of complex or biological organization, our framework offers a unified account of these phenomena within a structural realist ontology. In particular, we introduce a generative mechanism in which structure emerges through symmetry-breaking driven by the dynamical operator ($\mathcal{F}$), together with a maintenance condition that explains how such structures persist over time in non-equilibrium settings. In the richer, Prigoginean regime, this persistence is captured by a flux-dependent stabilizer subgroup ($H(s, \Phi)$) that reflects the role of energy, matter, and information gradients in sustaining organized states. The resulting framework, onto-dynamic structural realism, yields a formally well-defined and internally coherent account of the emergence and persistence of structure across multiple scales of the universe.

Keywords: onto-dynamic structural realism; ontic structural realism; Prigoginean; dissipative

§1 The Galilean and Noetherian assumptions

Our theory of structure begins with a Galilean assumption:

> (A1 or the Galilean assumption) The universe $\mathcal{U}$ has an objective, mind-independent structure and mathematics is the ideal language for describing this structure.

The core ideas behind A1 or the Galilean assumption may be derived from Galileo Galilei's defence of his philosophy of science in *The Assayer*:

> Possibly he thinks that philosophy is a book of fiction created by some man, like the *Iliad* or *Orlando Furioso* – books in which the least important thing is whether what is written in them is true. Well, Sig. Sarsi, that is not the way matters stand. Philosophy is written in this grand book – I mean the universe – which stands continually open to our gaze, but it cannot be understood unless one first learns to comprehend the language and interpret the characters in which it is written. It is written in the language of mathematics, and its characters are triangles, circles, and other geometrical figures, without which it is humanly impossible to understand a single word of it; without these, one is wandering about in a dark labyrinth. (Galilei et al., 1960, pp. 183–184)

Some scene-setting might be in order. The appearance of three comets in the skies over Europe in 1618 led Horatio Grassi, the Jesuit astronomer and mathematician writing under the pseudonym 'Sarsi', to defend the anti-Copernican view of celestial bodies as orbiting the Earth. Galileo's remarks, immediately directed at 'Sarsi' (Grassi), function as a critique in general of the scholastic reliance on rhetorical argument and textual authority and in particular of the Jesuit treatment of natural philosophy as a text-based tradition grounded in the work of Aristotle and later commentators. Nature, Galileo argues, cannot be treated in this manner, primarily because the universe is a book written in the language of mathematics. Galileo's central, positive claim functions as a concise manifesto of his philosophy of science, expressing in turn several connected ideas: nature having an objective structure that is independent of human thought and language; mathematics as the ideal language for describing this objective structure; geometrical relations (triangles, circles, and so on) as being relevatory of the underlying order of our universe; and all attempts to understand nature without mathematics as being tantamount to wandering in a labyrinth.

Galileo's manifesto furnishes us with a methodological argument in favour of a mathematical description of nature and its underlying structure. In accordance with A1, the structural regularities of nature might be regarded as mathematically invariant. Another assumption, the Noetherian assumption, can be lined up neatly alongside our Galilean assumption:

> (A2 or the Noetherian assumption) The underlying structure of the universe $\mathcal{U}$ is symmetrical and symmetry-breaking mechanisms allow observable, physical structure to emerge.

Symmetry refers to invariance (no change) under transformations (change) or – as the Nobel laureate Frank Wilczek (2016) more succinctly puts it –

change without change. Since symmetry is a mathematical notion, A2 is completely consistent with A1. Symmetry can be either continuous (continuous change without change) or discrete (non-continuous change without change). Since continuous symmetry can be represented algebraically by Lie groups, while discrete symmetry can be represented algebraically by finite groups, this lends credence to the claim of another Nobel laureate, Steven Weinberg, that 'the universe is an enormous direct product of representations of symmetry groups' (cited in Gallian, 2002, p. 150). Noether's (1918) theorem famously connects continuous symmetries in nature to conservation laws and conserved quantities: rotation symmetry is connected to the law of conservation of angular momentum (with angular momentum as the conserved quantity); translation symmetry is connected to the law of conservation of momentum (with momentum as the conserved quantity); and time-translation symmetry is connected to the law of conservation of energy (with energy as the conserved quantity).

In addition, physicists often describe systems using mathematical representations that have more degrees of freedom (redundancies) than the physical phenomena themselves. A gauge symmetry (change to redundancies without change to observable quantities) refers to the freedom to transform these mathematical descriptions without changing any measurable outcome. The full gauge symmetry group of the Standard Model of particle physics, describing three of the four known fundamental forces (electromagnetic, weak interactions, and strong interactions), is U(1) $\times$ SU(2) $\times$ SU(3). The U(1) gauge symmetry is associated with the electromagnetic force (with electric charge being conserved); the SU(2) gauge symmetry is associated with weak interaction (with weak isospin being conserved); and the SU(3) gauge symmetry is associated with strong interaction (with colour charge being conserved). Furthermore, the SU(3) gauge symmetry remains unbroken, and this explains why gluons (particles that mediate strong interaction) remain massless. By contrast, the SU(2) gauge symmetry is spontaneously broken by the Higgs mechanism (a symmetry-breaking mechanism), explaining why the W and Z bosons (particles that mediate weak interaction) can acquire mass at low-energy states (Englert and Brout, 1964; Higgs, 1964). Just as Noether's original continuous symmetries are associated with conservation laws in nature, the gauge symmetries are associated with the fundamental forces and – by extension – the force-carrying particles (including bosons and gluons).

Discrete symmetries, in turn, include parity symmetry or P (change to spatial coordinates by reflection without change), charge conjugation symmetry or C (change through replacement of particles by their antiparticles without change), and time reversal symmetry or T (change to the direction of time without change). According to the Soviet physicist Andrei Sakharov (1998), three conditions – known as the Sakharov conditions – must be satisfied for a matter/antimatter imbalance to arise in the early universe:

(C1) C and CP symmetry violation
(C2) Baryon number violation
(C3) Departure from thermal equilibrium

By C symmetry is meant the change through replacement of particles by their antiparticles without change. By CP symmetry is meant both the change through replacement of particles by their antiparticles and the change to spatial coordinates by reflection without change. According to the CPT theorem, CPT symmetry holds for all physical phenomena (Schwinger, 1951). The violation of CP symmetry is thought to account for the matter/antimatter asymmetry, baryogenesis, and a matter-dominated universe. The CPT theorem, in turn, implies that if CP symmetry is violated, then

T symmetry has to be violated to cancel out the violation of CP symmetry. The Wu experiment in beta decay provides experimental evidence for P symmetry violation (Wu et al., 1957), the Cronin-Fitch experiment in the decay of neutral kaons (K^0) for CP symmetry violation (Christenson et al., 1964), and the CERN-based CPLEAR experiment in kaons for T symmetry violation (Angelopoulos et al., 1998). The line of reasoning associated with the violation of discrete symmetries (C, P, and T) runs as follows:

> P1: The CPT theorem asserts that CPT symmetry is an exact symmetry: it holds for all physical phenomena.
> P2: The Cronin-Fitch experiment established the violation of CP symmetry.
> P3: If CPT symmetry is exact and CP symmetry is violated, then T symmetry must be violated as well. – from P1–P2
> P4: The CPLEAR experiment observed a violation of T symmetry consistent with the magnitude predicted from the known violation of CP symmetry.
> C: ∴ CPT symmetry remains an exact symmetry (as predicted by the CPT theorem). – from P3–P4

§2 The Banach-Tarski-Bueno assumption

Our theory of structure, informed by the Galilean (A1) and Noetherian (A2) assumptions (§ 1), aligns well with state-of-the-art physics. Indeed, recent research on generalized global symmetry, higher-form symmetry, higher-group symmetry, and non-invertible symmetry supports the view that symmetry, instead of being a mere property of the laws of physics, functions as a structural constraint on the space of possible theories (Córdova, Dumitrescu, and

Intriligator, 2019; Gaiotto et al., 2015).

This theory of structure aligns equally well with recent developments in the philosophy of science. Although new theories replace old ones over the course of the history of science, any acceptable new scientific theory must explain the empirical success of the old theory it replaces. This is known as the correspondence principle, and it presents us with a picture of the conservative character of scientific progress: new theories, far from discarding the results of older theories, extend the theories that they replace (Post, 1971). What ensures continuity across theories (older or newer), it might further be urged, is structure, as reflected in how the mathematical content of physical theories – Kepler's laws in the shift from the pre-Newtonian to the Newtonian paradigm; Newton's equations in the shift from the Newtonian to the Einsteinian paradigm; Maxwell's equations in the shift from classical to quantum electrodynamics; the Hamilton–Jacobi equation in the shift from classical to quantum mechanics; and so on – survives theory change (Worrall, 1989).

Ontic structural realism is the metaphysical thesis, arising within the philosophy of science, that structure is ontologically fundamental (French and Ladyman, 2010). Our theory of structure yields a version of ontic structural realism. At the same time, we do not wish to be committed to just any version of ontic structural realism. If their metaphysical account of structure remains insufficiently precise, then ontic structural realists will have to confront the collapse problem: what distinction, if any, can be made between mathematical and physical structure (French, 2014)? Our solution to the collapse problem involves the invocation of what may be termed the Banach-Tarski-Bueno assumption:

(A3 or the Banach-Tarski-Bueno assumption) Physical structures

$\mathcal{P}$ (structures that are compatible with the laws of physics) are a subset of mathematical structures $\mathcal{M}$ (structures that are logically consistent and describable in terms of the language of mathematics).

A3 is named after the Banach-Tarski paradox (Banach and Tarski, 1924) and Bueno's (2019) use of this paradox to infer that mathematical possibility does not entail physical possibility. According to this paradox, by accepting the axiom of choice – which permits the construction of non-measurable sets to which no consistent notion of volume can be assigned – it becomes mathematically possible in set-theoretic geometry to decompose a ball into a finite number of non-measurable point sets and then reassemble them into two balls identical to the original one. This is physically impossible, since the decomposition requires pieces that cannot correspond to any physically realizable object. In the real world, since any physical object is made of atoms, matter cannot be physically separated into non-measurable sets of points: the Banach-Tarski construction, though mathematically valid, cannot be realized in physics.

A3 allows us to provide a more precise metaphysical account of structure. Let $\mathcal{M}$ denote the space of all mathematically possible structures (sets, groups, topological spaces, fields, functions, and so on), including Banach-Tarski constructions. Let $\mathcal{P}$, by contrast, denote the space of physically possible structures. While everything physically possible is mathematically describable, not all mathematically possible structures have a physical analogue: $\mathcal{P} \subset \mathcal{M}$. The laws of physics function essentially as a filter or selection principle, choosing structures from $\mathcal{M}$ that are physically implementable. While pure mathematics allows for weird or exotic structures (for instance, non-measurable point sets), these structures get banned in physics due to energy, locality, and related constraints. The actual universe $\mathcal{U}$, in turn, is one physically possible structure in $\mathcal{P}$ that has been instantiated in reality: $\mathcal{U} \subset \mathcal{P} \subset \mathcal{M}$. The structure of the universe is therefore both mathematically describable and constrained by the laws of physics because it is mathematically possible, physically possible, and actually realized: it is an *ante rem* structure.[1]

§3 The Prigoginean assumption

Given the core commitments of our theory of structure, as described in § 2, the universe $\mathcal{U}$ can be modelled as a state space with lawful dynamics:

> $\mathcal{U} \equiv (S, \mathcal{F}, \mathcal{G})$, where S denotes the state space, $\mathcal{F}$ denotes the evolutionary operator (telling us how a state evolves over time), and $\mathcal{G}$ denotes the set of all the symmetries of the laws of nature (transformations such as rotations, translations, and so on that leave the laws unchanged)

Suppose that the universe evolves into a state $s \in S$ and we apply a symmetry $g \in \mathcal{G}$ to this state s. If the state s remains unchanged after the transformation, then the symmetry still holds for s. Otherwise, this symmetry is not preserved in s. The stabilizer subgroup H can be defined as the set of all transformations g in $\mathcal{G}$ that leave the state s unchanged:

$$H \equiv \{g \in \mathcal{G} \mid g \cdot s = s\}$$

[1] *Ante rem* structuralists defend a similar view: the physical universe is a mere subset of a pre-existing mathematical reality (Călinoiu, 2020; Hamlin, 2026; Shapiro, 1997, 2008).

The stabilizer subgroup H tells us which symmetries have survived after a particular structure or state has been chosen. Since $\mathcal{G}$ denotes the symmetries of the laws of nature and H denotes the symmetries of state s, when H is smaller than the full symmetry group $\mathcal{G}$, s only preserves a part of the original symmetries in $\mathcal{G}$ and the remaining, lost symmetries are said to be broken. Formally:

(Symmetry-breaking) $H \subsetneq \mathcal{G}$ (Michel, 1980; Weinberg, 1995)

The stage is now set for us to introduce the Prigoginean assumption:

(A4 or the Prigoginean assumption) When subsystems of the universe $\mathcal{U}$, governed by symmetric laws constrained by $\mathcal{G}$, are driven far from equilibrium by flows of energy and matter through them, dynamical instabilities can result in these subsystems settling into organized states whose stabilizer group H is strictly smaller than $\mathcal{G}$

A4 is a central assumption in the theory of dissipative structures (Prigogine, 1980; Prigogine and Nicolis, 1985; Prigogine and Stengers, 2018). At the start, the laws of nature governing the universe $\mathcal{U}$ possess symmetry $\mathcal{G}$. $\mathcal{F}$, in turn, describes the actual physical processes – including non-equilibrium dynamics – that move the universe through states in the state space S: $\mathcal{F}$:S $\rightarrow S$. As far-from-equilibrium subsystems of $\mathcal{U}$ experience dynamical instabilities, the non-equilibrium dynamics $\mathcal{F}$ can push these subsystems into symmetry-breaking states (realized states preserving only a subgroup H of $\mathcal{G}$). Structure therefore emerges when non-equilibrium dynamics $\mathcal{F}$ selects particular symmetry-breaking states ($\mathcal{G} \rightarrow H$) within the state space S.

A4 covers the most interesting and general cases: open systems, exchanging matter and energy with their surroundings, far from equilibrium and characterizable in terms of the emergence of new structure (crystals, cells, brains, ecosystems, and so on). This is where most of the complex, observable structure of the universe arises. As the selected state s arises from nonequilibrium dynamics under A4, we can view s as lying on a dynamical attractor of $\mathcal{F}$. The corresponding subgroup $H \subsetneq \mathcal{G}$ is then dynamically selected by this attractor. At the same time, it may be objected that the same outcome (symmetry-breaking or $\mathcal{G} \rightarrow H$) can be brought about by a mechanism other than dynamical attractors. For instance, closed systems near or at equilibrium can undergo symmetry-breaking, giving rise to particle masses (Higgs) and phase transitions (ferromagnets and crystals).

In the latter instance, the mechanism is not a dynamical attractor ($\mathcal{F}$ driving toward s, which lies on this attractor) but a potential minimization ($\mathcal{F}$ driving toward a fixed point or energy minimum). We can therefore accommodate equilibrium symmetry-breaking, as in the Higgs mechanism or ferromagnetic phase transitions, as a limiting case in which $\mathcal{F}$ drives the system toward a thermodynamic minimum that breaks $\mathcal{G}$. By contrast, A4 specifically concerns the richer, broader class of structure-generating processes in open systems, where $\mathcal{F}$ sustains symmetry-breaking states through the continuous dissipation of energy and against the thermodynamic tendency toward equilibrium. As Anderson (1972) has suggested, higher levels of organization and complexity (biological, neural, ecological, and so on) require symmetry-breaking that is not reducible to the limiting-case of equilibrium symmetry-breaking. This yields A4$'$ or the generalized symmetry-breaking assumption:

> (A4$'$ or the Generalized Symmetry-Breaking assumption) When subsystems of the universe $\mathcal{U}$, governed by symmetric laws con-

strained by $\mathcal{G}$, are subject to dynamical evolution $\mathcal{F}$ – whether driven toward thermodynamic equilibrium or sustained far from it by flows of energy and matter – instabilities can result in these subsystems settling into organized states whose stabilizer subgroup H is smaller than the full symmetry group $\mathcal{G}$. At or near the equilibrium (the limiting case), $\mathcal{F}$ selects symmetry-breaking states via potential minimization. Far from the equilibrium (the richer, Prigoginean case), $\mathcal{F}$ selects and maintains symmetry-breaking states via dissipative attractors.

In the limiting case, symmetry-breaking yields a static condition at equilibrium: $\frac{d}{dt}\Big|_{\mathcal{F}} s = 0$. By contrast and in the richer, Prigoginean case, symmetry-breaking yields a dynamic, steady-state condition under continuous flux: $\frac{d}{dt}\Big|_{\mathcal{F}(s;\Phi)} s \approx 0$, where Φ denotes the gradients of energy, matter, and information driving the subsystem. The '$\approx$' symbol implies how the dissipative structure continues to exchange energy, matter, and information with its surroundings to preserve its structure: the cascade of gradients Φ keeps the symmetry-breaking state alive. For dissipative structures in the richer, Prigoginean case, the stabilizer subgroup H is flux-dependent:

$$H(s, \Phi) \equiv \{g \in \mathcal{G} \mid g \cdot s = s \text{ under dynamics } \mathcal{F}(s; \Phi)\}$$

As we extend the evolutionary operator $\mathcal{F}$ to include driving gradients of matter, energy, and information $\mathcal{F}(s; \Phi)$, the stabilizer subgroup H becomes flux-dependent: $H(s, \Phi)$. The maintenance condition $\frac{d}{dt}\Big|_{\mathcal{F}(s;\Phi)} s \approx 0$ allows dissipative structures to maintain their local order – a dynamic, steady-state condition – by exchanging energy, matter, and information with their surroundings. The cascade of energy, matter, and information gradients Φ, in turn, is what sustains H over time in the Prigoginean case.

§4 Conclusion

In conclusion, our theory of structure relies on the following key assumptions:

> (A1 or the Galilean assumption) The universe $\mathcal{U}$ has an objective, mind-independent structure and mathematics is the ideal language for describing this structure.
> (A2 or the Noetherian assumption) The underlying structure of the universe $\mathcal{U}$ is symmetrical and symmetry-breaking mechanisms allow observable, physical structure to emerge.
> (A3 or the Banach-Tarski-Bueno assumption) Physical structures $\mathcal{P}$ (structures that are compatible with the laws of physics) are a subset of mathematical structures $\mathcal{M}$ (structures that are logically consistent and describable in terms of the language of mathematics).
> (A4 or the Prigoginean assumption) When subsystems of the universe $\mathcal{U}$, governed by symmetric laws constrained by $\mathcal{G}$, are driven far from equilibrium by flows of energy and matter through them, dynamical instabilities can result in these subsystems settling into organized states whose stabilizer group H is strictly smaller than $\mathcal{G}$

Our theory of structure identifies the universe as an *ante rem* structure that is mathematically possible, physically possible, and actually realized. Our theory therefore has much in common with ontic structural realism: the fundamentality of structure is reflected in our structural definition of the universe $\mathcal{U}$ in terms of the formalism (S, $\mathcal{F}$, $\mathcal{G}$); the ontologically basic nature of symmetries is reflected in the primitive nature of the symmetry group $\mathcal{G}$ in this formalism; and the derivative nature of objects is reflected in how dissipative structures emerge through symmetry-breaking ($\mathcal{G} \to H$, where $H \subsetneq \mathcal{G}$). At the same time, orthodox versions of ontic structural realism typically trade in fundamental physics (quantum field theory, gauge symmetries, and so on), with almost nothing being said about dissipative structures, far-from-equilibrium dynamics, and how complex and biological structures fit into ontic structural realism. My flux-dependent stabilizer subgroup $H(s, \Phi)$, drawing heavily on A4 or the Prigoginean assumption, is effectively a Prigoginean extension of ontic structural realism. Indeed, orthodox versions of ontic structural realism identify structure with symmetry but say little about how structure emerges or gets maintained. Our theory of structure introduces a generative mechanism through which structure comes to be ($\mathcal{F}$-driven symmetry-breaking) and a maintenance condition ($\frac{d}{dt}\Big|_{\mathcal{F}(s;\Phi)} s \approx 0$), explaining – in a way that these orthodox versions of ontic structural realism cannot – how dissipative structures can emerge, persist, and maintain themselves as real structural features of the universe, despite being far from equilibrium. Through our Prigoginean extension, our theory of structure is effectively an onto-dynamic structural realism, capable of accounting for the emergence and persistence of structure across all scales of the universe.

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