Scientia *et* Fides 14(1)/2026 ISSN 2300-7648 (print) / ISSN 2353-5636 (online)

Received: July 30, 2025. Accepted: March 11, 2026 DOI: http://dx.doi.org/10.12775/SetF.2026.006

Complexity at the Mesoscale: a Framework for Reflecting on Freedom and Vulnerability

CLODOMIRO CAFOLLA
Dipartimento di Fisica, Università di Pisa, Largo Pontecorvo, Pisa, Italia
Physics Department, Durham University, South Road, Durham, UK
miro.cafolla@gmail.com; clodomiro.cafolla@durham.ac.uk
ORCID: 0000-0002-8759-8775

Abstract: Condensed matter nanoscience and nanotechnology have profoundly transformed modern life, from advanced computing to biomedical applications. In condensed matter, the mesoscale, here understood as the regime spanning approximately nanometre to micrometre dimensions, marks a domain of structural complexity, in which surface effects, collective phenomena, thermal fluctuations, and nonlinear couplings often operate at comparable energy scales. In such a regime, no single interaction term typically dominates the effective physical description, and simplified asymptotic reductions give way to multiscale and numerically intensive modelling approaches. Observable behaviour may therefore not be exhausted by closed-form reduction without implying any suspension of underlying physical law.
Despite its scientific importance, the mesoscale has received comparatively little philosophical attention. Philosophical and theological reflection has traditionally concentrated on the cosmic scale, where gravitational order suggests intelligibility, or on the quantum scale, where formal indeterminacy has prompted discussions of contingency and divine action. By contrast, the mesoscale has received comparatively less attention, even though biological organisation and embodied human existence crucially depend upon processes operating within the mesoscale regime.

This paper proposes that mesoscale complexity offers a fruitful context for revisiting questions of freedom, suffering, and the privation of good. Rather than opposing scientific explanation and metaphysical meaning, the mesoscale is presented not as a distinct ontological realm, but as a structurally intermediate regime in which stable laws and dynamical openness coexist, thereby inviting renewed dialogue between philosophy of science, natural philosophy, and theology.

Keywords: nanoscale physics; nanoscience; nanotechnology; mesoscale; human freedom and God's action; determinism; quantum theory; chaos; randomness; complexity.

Contribution: This study explores the mesoscale as a scientifically grounded domain of structurally open, lawfully constrained systems with a complex interplay of interactions of similar magnitude. It develops this framework as a relatively unexplored site for reflection on human freedom, vulnerability, and the classical theological notion of *privatio boni*, contributing to the dialogue between science, philosophy, and theology from a critical realist perspective.

Use of AI: Language editing benefited in part from AI tools. All the scientific content and interpretation are the sole responsibility of the author.

Introduction

The relationship between science and religion has long evolved alongside developments in the natural sciences. From Newtonian mechanics onward, advances in physics, chemistry, and the life sciences have repeatedly reshaped philosophical reflection on intelligibility, causation, order, and design. Each major theoretical transformation has prompted renewed consideration of how empirical description and metaphysical interpretation relate to one another (Wilkinson 2025).

Central to scientific inquiry is the notion of length scale (Wilson 1979). Length scale does not designate distinct substances or ontological strata, but regimes within which different effective descriptions, approximations, and dominant interactions become salient (Batterman 2001). High-energy accelerators probe nuclear phenomena on the order of femtometres (10^{-15} m) (Griffiths 2020), while astronomical observations analyse electromagnetic signals from objects separated by light-years

(Carroll 2017). At different scales, distinct interactions and modelling strategies tend to become dominant or effective, not because reality fragments into disconnected domains, but because different terms in physical descriptions acquire relative prominence.

In condensed matter systems, the regime spanning approximately nanometre (10^{-9} m) to micrometre (10^{-6} m) dimensions (here referred to as the mesoscale) marks a domain in which surface effects, collective behaviour, thermal fluctuations, and nonlinear couplings frequently operate at comparable magnitudes. In such systems, no single interaction term typically dominates the effective energy landscape or dynamical description, and asymptotic simplifications based on scale separation may lose accuracy. The result is not a breakdown of physical law, but a regime in which multiscale coupling, boundary sensitivity, and context-dependent organisation play central roles in shaping observable behaviour (McLeish 2016).

Biological organisation and embodied human existence depend crucially on processes unfolding within such a regime (Koeppen 2023). For this reason, mesoscale phenomena offer a promising site for philosophical reflection. This paper investigates whether, while remaining fully consistent with established physical theory, mesoscale dynamics provide a structurally suggestive context for reconsidering themes of order, freedom, and suffering within Christian theological reflection.

The structure of the paper is as follows. Sections 1 and 2 outline the relevant scientific background, with the former focusing on determinism, quantum theory, and nonlinear and chaotic dynamical systems, and the latter examining symmetry and order across classical and quantum models. Section 3 then analyzes structural complexity and interaction interplay at the mesoscale, while Section 4 considers how such structural features may inform philosophical discussions of moral freedom and responsibility. Section 5 examines how vulnerability and suffering within physically contingent systems intersect with Christian theological accounts of evil. Section 6 revisits epistemic limitations as highlighted by mesoscale science. Section 7 addresses tensions between physical contingency and theological interpretation within Christian theological reflection, and Section 8 proposes critical realism as a framework capable of integrating these domains. Section 9 concludes with reflections on sustained dialogue between science, philosophy, and theology.

1. Determinism, quantum uncertainty, and chaos theory

Science has long been associated with a precise, rational framework for understanding the universe, one that aspires to generate mathematically exact predictions. This ideal is epitomised by the laws of motion and gravitation formulated by Isaac Newton, which allow for remarkably accurate calculations of planetary or satellite trajectories. Central to this classical worldview is the principle of nomological determinism, with causal determinism often treated as its natural corollary: the belief that, given complete knowledge of a system's present state and the laws of nature, its future follows with necessity and could, in principle, be predicted with certainty. This deterministic paradigm dominated classical mechanics from the seventeenth to the nineteenth century (Hoefer 2003; Müller 2018; Wilkinson 2025).

Within classical mechanics, determinism entails that the future evolution of a system is fully specified by its present state and governing laws. This ontological determinacy does not necessarily imply practical predictability, which depends on epistemic access to initial conditions and computational tractability, but it underwrites the ideal of a fully law-governed cosmos. Within this perspective, divine action was often interpreted in rational terms: the mathematical harmony and order observed in nature suggest a Creator whose designs are discoverable and comprehensible by the human intellect (Polkinghorne 2000). Whether one sees God as necessary for sustaining natural laws, as Newton did, or as having established a self-sufficient universe akin to a clockwork mechanism, as suggested by thinkers like Leibniz, the underlying idea remains the same: the world is governed by rational laws expressed through mathematics and set by a divine Creator (Leibniz 1710; Wilkinson 2025). Even miracles, in Newton's view, need not be seen as violations of natural law, but rather as rare or exceptional events that, while not fully understood, do not contradict the rational structure of the universe (Wilkinson 2025).

Developments in twentieth-century physics have challenged the deterministic assumptions associated with classical mechanics. The formulation of the uncertainty relations in quantum theory, as articulated by Werner Heisenberg (1958), establishes principled limits on the simultaneous precision with which certain pairs of physical observables (such as position and momentum) can be specified. In standard collapse interpretations of quantum mechanics, even when the quantum state is precisely defined, measurement outcomes are described probabilistically rather than deterministically (Heisenberg 1958). Other interpretations, such as the Everettian account defended by David Wallace (2012), retain determinism at the level of the universal wavefunction while reconceiving the status of measurement outcomes. Although these developments do not entail a single metaphysical conclusion, they have prompted renewed philosophical reflection on causality, openness, and the structure of physical law. Various scholars, including William Pollard, have argued that quantum indeterminacy may provide conceptual space for accounts of divine action that do not require violations of physical law (Pollard 1958). On such models, divine action is understood as operating through the indeterministic features described by quantum theory without suspending or violating physical regularities (Wilkinson 2025).

Further limitations of practical predictability within nomological determinism arise in chaotic systems (McLeish 2016). In contrast to quantum indeterminacy, chaos concerns deterministic systems that exhibit extreme sensitivity to initial conditions. Weather dynamics provide a paradigmatic example: governed by precise physical laws, such as the Navier-Stokes equations, even minute uncertainties in initial parameters, including temperature, pressure, humidity, and wind velocity, can lead to dramatically divergent outcomes, rendering long-term prediction practically impossible (Lorenz 1963). Some theologians have interpreted the lawful yet practically unpredictable behaviour of chaotic systems as suggestive of a form of openness compatible with divine providence and human freedom; from a strictly physical standpoint, however, chaotic dynamics remain deterministic: unpredictability arises from sensitivity to initial conditions rather than from ontological indeterminacy (Polkinghorne 2000).

This intersection of determinism and unpredictability is particularly illustrative at the mesoscale. Turbulent fluids, ecosystems, and neural networks often exhibit emergent collective behaviour, in which larger-scale patterns arise from many-body interactions and are not straightforwardly deducible without full dynamical analysis. A particularly striking example is found in neural networks: the human brain contains roughly 86 billion neurons interacting via complex synaptic connectivity (Herculano-Houzel 2009). These interactions display nonlinear and sometimes chaotic or near-chaotic dynamics, where small perturbations, genetic, environmental, or developmental, can profoundly alter cognitive and behavioural outcomes (Breakspear 2017; Longo 2022; Seitz 2024). Within this dynamic substrate, consciousness is often modelled or described as an emergent phenomenon, arising from coordinated activity across large-scale brain networks (Dehaene 2011; Tononi 2016).

The trajectory from classical determinism to quantum theory and chaos thus expands the conceptual landscape of scientific explanation. Rather than converging on a single explanatory scheme, contemporary physics operates through multiple formally precise but scale-sensitive models. The next section examines symmetry and order as recurring structural features across these frameworks.

2. Symmetry, order, and God

From the earliest days of natural philosophy, thinkers have reflected on the intelligibility of the cosmos. Plato, for example, associated beauty with harmony and balance, believing that they reflected ideal rational structures (Plato, *Timaeus;* Abbagnano 2001). This enduring human responsiveness to patterned regularity has shaped aesthetic sensibilities as well as scientific and theological reflection. It is important, however, to distinguish between aesthetic appreciation, formal physical description, and theological interpretation. Among the features of nature that have frequently attracted such attention are symmetry and order.

In both physics and mathematics, symmetry and order function as analytical concepts for describing structural regularity. In physics, symmetry denotes the invariance of governing equations under specified transformations such as spatial translation, spatial rotation, time translation, or gauge transformation. What remains invariant is the formal structure of the laws, not necessarily a particular physical configuration. Through Noether's theorem, continuous symmetries are associated with conserved quantities: time-translation invariance corresponds to conservation of energy, spatial translation to conservation of linear momentum, and rotational invariance to conservation of angular momentum (Hanc 2004).

Order, in physical contexts, refers to the formation of structured configurations within systems. Such order frequently arises through symmetry breaking, when a highly symmetric state becomes unstable and transitions into a state of reduced symmetry characterised by distinguishable structure. Examples include magnetic ordering in ferromagnetic materials (Wilming 2017; Šmejkal 2022), crystallisation in colloidal systems (Jones 2002), and large-scale structure formation in cosmology (Planelles 2015).

In mathematics, symmetry is formalized through group theory, while order may designate structured relations or hierarchical organisation within formal systems (Weyl 1952). Together, these concepts provide tools for articulating regularity and constraint across diverse domains, from classical mechanics to particle physics, as well as within formal mathematical systems (Stewart 2010).

The invariances described above are exemplified in classical gravitational theory. In the idealised Newtonian two-body problem, the equations governing motion are invariant under time translation, spatial translation, and spatial rotation. These conserved quantities account for the stability and periodicity of orbital motion and allow celestial trajectories to be described with high mathematical precision. Such formal coherence contributed to the historical perception of celestial mechanics as a paradigm of intelligibility. Early modern figures, such as Johannes Kepler, interpreted this mathematical regularity within a theological framework, describing scientific inquiry as "thinking God's thoughts after Him" (Koestler 1959). At atomic and subatomic scales, symmetry also plays a central role. The Standard Model of particle physics is formulated in terms of gauge symmetries that constrain permissible interactions and organize elementary particles into systematic classifications (Langacker 2017; Zee 2016).

3. At the mesoscale: randomness or structural complexity?

From a theological perspective, the human capacity to recognize and articulate such structural regularities has itself been a subject of reflection. Within Christian theology, the doctrine of the Logos affirms that creation is grounded in divine rationality (John 1:1; Craig 2008). This metaphysical foundation interprets the intelligibility of nature and the human ability to formulate mathematical laws as consonant with a broader framework in which reality is rooted in divine reason. At the same time, mathematical articulation does not exhaust the significance of creation. Symbolic, poetic, and contemplative forms of understanding disclose additional dimensions of meaning beyond formal expression. What distinguishes mathematical and physical law is their universality: Maxwell's equations or Einstein's field equations retain structural coherence across linguistic and cultural contexts when shared notation is adopted, reflecting a form of transcendent rationality that transcends human particularity.

If symmetry and invariance articulate the structural regularities of physical law, condensed matter mesoscale systems frequently display the consequences of reduced symmetry, finite size, and boundary constraint within localised domains. Idealised bulk models often assume translational invariance, homogeneity, or negligible surface contributions. In mesoscale regimes, however, surface-to-volume ratios increase and interfacial terms may contribute significantly to the system's effective free energy. As a result, structural heterogeneity, nonlinear coupling, and competing interactions become dynamically prominent within otherwise standard physical frameworks.

A striking example comes from tribology, that is, the study of friction, lubrication, and wear (Mate 2025). At nanoscale and microscopic interfaces, small variations in surface chemistry and geometry can produce markedly different outcomes. Water, for instance, acts as a plasticiser in human skin, softening tissue and increasing friction when a blade is applied. By contrast, the hydrophobic microstructure of shark skin reduces viscous drag by guiding water flow along aligned dermal scales (Mate 2019; Qin 2025). In such cases, boundary terms that are negligible in bulk descriptions become dynamically consequential in influencing the tribological properties of water on different surfaces.

Protein and polymer self-assembly provide a further example. Proteins, linear chains of amino acids, fold into intricate three-dimensional conformations governed by electrostatic, van der Waals, and hydrophobic interactions. Although the amino acid sequence constrains the final structure, its stable configuration cannot generally be predicted analytically and remains computationally demanding from first principles, because the associated energy landscape is high-dimensional and rugged. Minute fluctuations influence folding pathways, and small perturbations may lead to alternative metastable states and non-functional enzymes (Dobson 2003; Tsuboyama 2023). This difficulty reflects combinatorial complexity and nonlinear coupling among many degrees of freedom rather than any suspension of underlying physical laws.

Complexity becomes especially visible in nanoscale heterostructures, where interfacial effects dominate bulk behaviour. Symmetry group theory classifies 122 magnetic point groups, yet this taxonomy alone does not uniquely determine the emergent properties of layered systems formed from materials with differing symmetries (Giustino 2014). In $LaAlO_3/SrTiO_3$ heterostructures, for example, combining two non-magnetic insulators yields unexpected conductivity, magnetism, and even superconductivity (Zubko 2011). These phenomena arise from a combination of different interactions: electron delocalisation, lattice distortions, interfacial charge redistribution, and spin interactions that become particularly significant at boundaries. As Wolfgang Pauli remarked, “God made the bulk; the surface was invented by the devil” (Ligler 2013).

This aphorism captures the modelling challenge of boundary-dominated systems: structural discontinuities concentrate several interacting effects within confined regions.

Underlying many of these phenomena is entropy, a measure of the number of microscopic configurations compatible with a macroscopic state. Entropy provides a statistical basis for irreversibility: in isolated systems, entropy increase corresponds to the overwhelmingly probable evolution toward macrostates occupying larger regions of phase space. In other words, processes that increase entropy are thermodynamically favoured in isolated systems, while those that decrease it require external work (Blundell 2010). Entropy operates across all scales. At the cosmological level, discussions of heat death concern the evolution of total entropy in an expanding universe (Chaisson 2001; Layzer 1990; Lineweaver 2013; McCabe 2017; Patel 2017). In quantum theory, the situation is more complicated: while the global entropy of a closed quantum system remains constant, entropy increase characterises subsystems through entanglement or environmental coupling (Esposito 2010; Goold 2016; Nielsen 2010).

At the mesoscale, entropic processes tend to become experimentally observable over more accessible timescales. In tribological systems, frictional shear produces local heating and wear debris, converting mechanical work into more disordered motion (Mate 2019). In thin films and nanoscale heterostructures, atoms migrate to minimize free energy; grain boundaries coarsen; domain walls distort, generating random variations in anisotropy and coercivity (Cullity 2011). In biological membranes, thermal undulations randomise receptor exposure and signaling (Allison 2021). Living systems maintain local organisation by exporting entropy to their surroundings; biological ageing involves cumulative molecular damage and declining repair efficiency within thermodynamic constraints (Banasik 2021).

While such examples might suggest that the mesoscale is a realm of ontological randomness and epistemic failure, this is not the case. Mesoscale systems remain fully governed by the same quantum, statistical, and continuum principles that apply at atomic and cosmological scales. However, the configurational and dynamical degrees of freedom available to mesoscale systems, together with their multiple interfacial interactions, mean that their collective behaviour rarely reduces to a single dominant interaction. At atomic and subatomic scales, interactions are typically described within quantum field theory, where gauge symmetries constrain possible interactions (Langacker 2017). At astronomical scales, gravitational interaction becomes dynamically dominant to first approximation in many large-scale systems (Carroll 2017). At intermediate scales, electromagnetic forces remain fundamental, while thermal fluctuations, geometric constraints, environmental coupling, and collective many-body effects significantly influence observable behaviour. Biological systems vividly exemplify this layered coupling. Cardiac function, for instance, depends simultaneously on electrical excitation of myocardial tissue, biochemical signaling pathways, fluid dynamics of blood flow, thermal regulation, and hydrostatic pressure gradients (Longo 2022; Koeppen 2023). In some medical contexts, nuclear decay processes may also interact with surrounding tissues, introducing additional physical effects consistent with known physics (Longo 2022; Schofield 2021).

It is, however, important to emphasise that these structural features are not unique to the mesoscale. Boundary-dominated phenomena and the interplay of multiple interactions appear across many domains of physics. In gravitational theory, black hole thermodynamics associates entropy with horizon area rather than volume (Wald 2001); in early-universe cosmology, symmetry-breaking transitions generate domain walls and other topological defects (Vilenkin 1994). Likewise, nonlinear coupling is fundamental to the Einstein field equations themselves (Carroll 2019), and competing interactions structure planetary climate systems, where radiative forcing, fluid turbulence, gravitational stratification, and rotational dynamics interact to produce sensitive dependence on initial conditions (Vallis 2017).

Thus, the mesoscale does not introduce a distinct ontology of matter. Rather, it is characterised by the conjunction of structural features already well established in many-body and non-equilibrium physics- such as sensitivity to boundary conditions, nonlinear coupling, and the coexistence of interactions of comparable magnitude within spatially and temporally finite regimes. In such settings, interactions are often comparable in magnitude and mutually coupled, and collective behaviour arises from their coupled dynamics rather than from a single parametrically dominant contribution. Because these regimes typically occur at length, energy, and time scales accessible to laboratory manipulation, the interplay among interactions can be systematically investigated by varying geometry, composition, boundary conditions, or applied fields (Jones 2002; Cullity 2011; Mate 2019). The mesoscale therefore does not constitute a privileged domain of being, nor does it require novel physical principles, but it functions as a regime in which relational structure becomes experimentally tractable without departing from established physical theory.

4. A hypothesis: from mesoscale structural complexity to moral freedom

When multiple interactions of comparable magnitude operate simultaneously, system behaviour cannot generally be well approximated by a single dominant contribution, but is shaped by the coupled influence of boundary conditions, nonlinear feedback, and competing interactions. In such regimes, systems may access multiple stable or metastable configurations, with trajectories unfolding within high-dimensional phase spaces characterised by path dependence.

Biological systems exemplify this regime. Networks of neurons, enzymes, and genes display adaptive plasticity, dynamically reorganising in response to stimuli, encoding memory, and modifying behaviour across time (Koeppen 2023). Neural plasticity, in particular, demonstrates how a physical substrate can sustain a vast range of possible connectivity patterns and response profiles shaped by experience and environmental interaction (Kandel 2012; Longo 2022; Koeppen 2023). These adaptive dynamics reflect lawful biochemical and electrophysiological processes, yet they unfold within a landscape of multiple dynamically admissible outcomes. Mesoscale structural complexity may thus supply material conditions under which conscious and deliberative processes can be instantiated without positing new physical principles.

Entropy provides the statistical framework within which such processes unfold. The second law of thermodynamics states that the total entropy of an isolated system does not decrease (Blundell 2010). Biological organisms, as open systems, maintain local order through continuous energy exchange with their environment, exporting entropy while sustaining organised structure (Koeppen 2023). Because mesoscale processes tend to occur on spatial and temporal scales more easily accessible to observation, thermodynamic irreversibility becomes experientially salient: materials age, structures degrade, and biological systems undergo cumulative structural change. Within such a temporally asymmetric and structurally open domain, biological systems sustain alternative courses of action that remain causally embedded within lawful processes while not being straightforwardly reducible to a single dominant physical interaction. While thermodynamic irreversibility does not generate moral meaning, it grounds the reality of history and renders human action causally efficacious and ethically consequential.

5. Evil and suffering in the mesoscale perspective

The structural multiplicity described above permits the emergence of highly ordered configurations, from interfacial magnetic textures to complex biological organisms, but it also entails vulnerability. Where system stability depends upon the coordinated balance of several interactions of comparable magnitude, disruption of that proportional balance can lead to loss of coherence or functional breakdown (Was 2007). This structural feature does not itself constitute evil; it describes a condition under which finite and contingent forms of order must be continuously maintained.

At the physical level, this can be illustrated by skyrmions in thin-film magnetic systems. Skyrmions are nanoscale vortex-like spin textures stabilized by a balance among symmetric exchange interaction, antisymmetric Dzyaloshinskii–Moriya interaction, magnetic anisotropy, and Zeeman energies (Tokura 2020). A skyrmion corresponds to a local energy minimum maintained by this balance. If one interaction becomes sufficiently dominant relative to the others, the noncollinear configuration ceases to be energetically favourable, and the system may relax toward a more uniform magnetic state. This transition is simply a shift in energetic equilibrium, but it may still result in a potential loss of topologically encoded information in the skyrmion configuration, illustrating how relational order depends upon sustained proportional coordination among interacting terms.

A similar structural logic appears in biological systems, but here the existential stakes differ. Living organisms exhibit functionally integrated organisation directed toward the cooperative functioning of the whole. When this coordination fails, the result is not always a mere reconfiguration as in the case of physical systems, but it can be genuine privation in the classical Augustinian sense of *privatio boni*, that is, the absence of a due perfection (Augustine *Confessions*, Book VII; Augustine *The Enchiridion on faith, hope, and love*, ch. 12–14; Boucher 2025). Cancer, for instance, arises when cellular proliferation escapes regulatory constraints, no longer serving the organism's integrative order (Hanahan 2011; Banasik 2021). Likewise, protein misfolding can disrupt biological function despite being governed by the same physical laws as correct folding (Dobson 2003; Tsuboyama 2023). Similarly, in consciousness, disproportionate weighting within regulatory networks of the brain, whether psychological stimuli, chemical signals, or external events, can dominate awareness, leading to neuropsychiatric disorders such as obsessive fixation or delusion (Friston 2010). These dysfunctions are measured relative to the organism's integrated biological and cognitive ends (Simpson 2025), reflecting failures of relational proportion within systems naturally oriented toward cooperative unity. Theologically, these are instances of natural evil, privations of due order in living beings (Aquinas, *Summa Theologiae* I, q. 48, a. 5).

Entropy clarifies the physical horizon within which such vulnerabilities occur. As noted earlier, the second law of thermodynamics states that in a closed system entropy tends to increase, corresponding to the dissipation of free energy and the reduction of capacity to perform organised work (Blundell 2010). Entropy is not evil, nor is it privation in the metaphysical sense, but it characterises the thermodynamic constraints under which finite systems operate. Complex structures persist only by maintaining energy gradients and exporting entropy to their surroundings. When such gradients can no longer be sustained, organised complexity degrades. In living systems, this degradation can manifest as genuine privation: degeneration, and ultimately death. Entropy forms the physical horizon within which the long-term vulnerability of organised systems is unavoidable in a finite world. Within this physical horizon, entropy is also related to the arrow of time, which brings ageing and loss, but it also permits irreversible processes through which development and change occur. This thermodynamic trajectory has also been interpreted in eschatological terms as a horizon for renewal that transcends human history: Teilhard de Chardin envisioned irreversible decay as pointing toward the Omega Point, a final convergence in Christ (Teilhard de Chardin 1955), while Moltmann saw it as a signpost toward Parousia, the renewal of creation (Moltmann 1996).

Suffering, in this framework, can be understood as the experiential correlate of privation in beings capable of sensation and consciousness. When the relational order proper to an organism or person is disrupted, this loss can be experienced as physical pain or psychological distress. Humans, as mesoscale beings embedded within complex biological and social networks, inhabit a domain characterised by structured contingency, incomplete information, and genuine freedom. The same relational conditions that permit flourishing also entail fragility. Vulnerability, on this account, arises not from a defect in physical law but from the finite, energetically sustained, and proportion-dependent character of complex relational order. This perspective does not claim to resolve the philosophical problem of evil, but it suggests that the vulnerability intrinsic to complex relational order provides a natural context within which the reality of suffering can arise in a finite world.

6. Epistemic limits at the mesoscale

Epistemologically, the mesoscale offers a vivid illustration of the limits of scientific intelligibility. Unlike highly idealised deterministic systems, whose symmetry often permits analytical closure, mesoscale phenomena typically involve the interaction of multiple physical processes whose coupled behaviour typically may not be exhausted by unified closed-form description, not because governing laws fail, but because multiple interaction terms contribute with comparable magnitude. In such regimes, where no single contribution dominates the effective energy landscape, modelling therefore relies on approximate, scale-bridging strategies, often combining numerical simulation, coarse-graining, renormalisation techniques, and phenomenological parameterisation (McLeish 2016).

Epistemic limitations are not unique to the mesoscale. Open problems persist across physics, from gravitation to quantum field theory (Giddings 2025; Heller 2025). The epistemic salience of the mesoscale is, however, amplified by its anthropological and technological centrality (López Cambronero 2023; Martínez-Lucena 2023; Peters 2024; Webster 2024). Most biological organisation operates at mesoscale dimensions (Koeppen 2023). Likewise, several technologies that have reshaped contemporary society (George 2024; Mullins 2025), i.e. semiconductor junctions thin films, nanostructured materials, polymer composites, derive their functionality from engineered interfacial effects at the nanoscale (Mate 2019). The mesoscale also renders epistemic limitations especially tangible, not uniquely, but with particular experimental immediacy, because relational complexity often manifests at length and time scales closer to direct human observation and manipulation.

Wolfgang Pauli's aphorism, "God made the bulk; the devil made the surface" (Ligler 2013), captures the practical experience of researchers working at mesoscale interfaces, where symmetry reductions and homogeneity assumptions frequently fail. The remark is methodological and not theological. Bulk systems can be approximated as continuous media with uniform properties, allowing their behaviour to be described by stable governing equations. Classical celestial mechanics, for example, models planets as point masses or homogeneous spheres, where scaling mass alters magnitude but not qualitative dynamical structure (Young 2016). Similarly, subatomic particles can often be treated as idealised entities governed within well-defined quantum field theory formalisms (Griffiths 2020).

In contrast, condensed matter mesoscale systems commonly involve interfacial coupling between heterogeneous components. As previously discussed, thin-film heterostructures, for instance, can exhibit emergent magnetic or conductive properties not present in the bulk constituents (Zubko 2011; Mate 2019). These effects do not indicate a suspension of physical law but rather reflect the interaction of multiple lawful processes whose effective parameters depend on boundary conditions and mutual constraints. Thus, while the fundamental governing equations remain valid, their practical application becomes inherently context-dependent and non-autonomous in a modelling sense, insofar as effective parameters depend sensitively on environmental and boundary conditions (McLeish 2016). Consequently, no single closed deterministic formulation tends to suffice in capturing mesoscale behaviour, even though it remains fully embedded within established physical theory (Cartwright 1999; Ellis 2012).

From an epistemological standpoint, the mesoscale thus contributes to highlighting a methodological tension: the persistent gap between fundamental law and layered effective description in systems whose complexity exceeds compression into a single, simple analytic framework. This tension concerns epistemic opacity rather than dynamical indeterminacy, and it should not be conflated with moral or theological categories of suffering. Deterministic equations may underlie the dynamics, even where predictive description proves difficult. The limitation therefore lies in the structure of scientific description rather than in the ontological structure of reality itself.

7. The mesoscale from a Christian perspective: no simple answers

The structural and epistemological features highlighted in mesoscale systems- in particular, interfacial coupling, sensitivity to boundary conditions, dense interaction networks without a single dominant term, and their coexistence with structural fragility- resonate with broader reflections on finitude. These features do not constitute a distinct ontological tier, nor do they establish a special regime of being. Rather, they exemplify, by analogy, the lawful, yet contingent and vulnerable structure characteristic of a finite creation.

Christian theology has long wrestled with contingency, vulnerability, and suffering (Moltmann 1972; Messori 1979; Herce 2024; Oviedo 2024; Roszak 2024; Wahlberg 2024). Some have argued that creation must be sufficiently ordered to sustain coherent existence, yet open enough to permit freedom and moral growth (Hick 1966; McCord Adams 1999). Yet not all suffering arises from human action: natural disasters, from the Lisbon earthquake of 1755 to modern pandemics, have challenged theological confidence in providence (Voltaire 1759; Ormerod 2022). The Christian tradition ultimately locates its response not in theoretical justification but in the historical event of the Cross. As Karl Barth insists in *Church Dogmatics* II/1 (§31–33), God's answer to suffering is not a speculative theodicy but self-involvement. In the Gospels, Christ does not offer a conceptual solution to suffering; he undergoes it (Matthew 27:46; cf. Psalm 22:1). Divine solidarity precedes explanation (*Gaudium et Spes* 22; Messori 1979; Herce 2024).

Within the Christian framework, the mesoscale may thus serve as an analogy illustrating how lawful interactions can generate both structural complexity and fragility within finite systems. Suffering is neither dismissed nor justified; it remains, in the Augustinian sense, a genuine privation, a real absence of due good within creatures ordered toward flourishing. The Christian claim is not that complexity justifies suffering, but that divine love is disclosed within a world where lawful processes can give rise to both beauty and loss (Roszak 2024; Wilkinson 2025).

From this standpoint, the world's lawful regularity is itself a condition of providence. Classical Christian theology affirms that divine providence operates through, rather than in competition with, natural causes. As St Thomas argues (*Summa Contra Gentiles* III.100–103), divine action does not negate secondary causality but sustains it. Some contemporary Christian thinkers have further explored this theme, suggesting that features such as quantum indeterminacy or dynamical complexity might provide conceptual models for understanding divine action that does not compete with physical causality (Polkinghorne 1998a; Polkinghorne 1998b; Davies 2007; Wilkinson 2025). Similarly, the mesoscale, with its intersection of competing interactions and sensitivity to boundary conditions, may function as a suggestive analogy for how lawful processes can remain structurally open in the sense that, under determinate physical laws, multiple trajectories may remain dynamically admissible.

This should not be taken to imply that divine action is localised at this scale, or that openness is confined to a particular ontological layer. Rather, the mesoscale offers a particularly vivid manifestation, among many, of a pervasive feature of finite creation: its lawful, yet contingent structure. Within such a framework, delicate balances among interacting processes may give rise either to constructive emergence or to the loss of unrealised possibilities. The mesoscale may therefore represent one of the many loci in which created openness is manifest and thus conceptually hospitable to divine creativity. As John Polkinghorne and others have argued, God's "silent providence" operates within the lawful openness of the world, influencing outcomes without violating its integrity, whether at the quantum level, through the amplification processes characteristic of chaotic systems, or through the dynamic interplay of competing interactions (Polkinghorne 1998a; Polkinghorne 1998b; Wilkinson 2025).

8. The mesoscale: some notes on a critical realist account

Human inquiry operates within a persistent tension between epistemic limitation and the aspiration to full intelligibility, a tension that concerns the relation between what exists independently of us and what we are able to know of it. This tension frames the long-standing debate concerning the relation between ontology and epistemology.

Medieval debates between realism and nominalism already exposed this divide: were linguistic signs mere conventions, or did they correspond to the very essence of things (Abbagnano 2001)? The question at stake was whether cognition participates in an independently structured order of being or instead organises experience according to its own conceptual resources. Modern philosophy reconfigured this tension: for Kant (1781), the *noumenal* world ("the thing in itself") remains ultimately inaccessible, as human knowledge is mediated by innate categories that structure experience of phenomena. In the twentieth century, logical positivism approached the issue differently by proposing a criterion of cognitive significance according to which a synthetic statement is meaningful only if it is empirically verifiable or confirmable (Abbagnano 2001). This move did not resolve the ontological question so much as bracket it by restricting philosophical analysis to empirically testable claims.

Contemporary philosophy of science presents a more differentiated landscape than a simple opposition between realism and anti-realism. Positions range from scientific realism, which affirms that scientific theories refer to mind-independent structures of the world (Psillos 2005), to more cautious variants such as structural realism, which preserve ontological commitment while restricting it to relational structure in response to historical theory change (Worrall 1989), as well as to explicitly anti-realist positions such as constructive empiricism, according to which the aim of science is empirical adequacy rather than truth concerning unobservable entities (van Fraassen 1980).

Within this spectrum, critical realism, developed by Roy Bhaskar (1975) and extended in the philosophy of science and theology, offers a mediating position. It affirms that reality exists independently of our perception (ontological realism) while acknowledging that knowledge is always situated, mediated, and fallible (epistemic relativity). Critical realism stands between the epistemic optimism of classical realism and more radical constructivist or anti-realist accounts by holding that knowledge constitutes a provisional and mediated grasp of a reality that exceeds our conceptual schemes. Causation, on this view, is grounded in generative mechanisms: real structures and powers that produce observable events, though they may themselves be unobservable and may be masked or counteracted by other mechanisms. Scientific inquiry therefore aims not merely at describing empirical regularities but at identifying and refining accounts of such mechanisms.

Critical realism provides a useful framework for interpreting mesoscale science. Systems at intermediate scales illustrate regimes in which multiple mechanisms interact without a single dominant contribution to the effective dynamics. In such contexts, mechanisms may reinforce or counteract one another, and no single interaction term fully determines system behaviour; outcomes depend on the context-sensitive interplay of comparable contributions. Phenomena such as self-assembly in nanostructures, capillary-driven patterning, or frictional behaviour at tribological interfaces demonstrate that causal outcomes are highly condition-dependent. The same mechanism may yield divergent results under slightly altered boundary conditions, while others may remain unactuated or masked by competing processes. The absence of constant empirical regularities does not therefore entail the absence of causal structure. Similar explanatory structures appear in biomedical science. Symptom clusters may correlate with specific pathologies, for example, fever, nocturnal sweating, and weight loss in lymphoma (Lewis 2020); however, explanation rests not solely on statistical association but ultimately depends on identifying interacting physiological and biochemical mechanisms operating across multiple levels of organisation (Green 2025).

Epistemically, mesoscale research also illustrates limits of direct transparency. Descriptions are model-dependent and approximate. Techniques such as coarse-graining, multiscale modelling, and machine-learning inference aim to represent effective parameters and latent structures that capture relevant causal patterns. Within a critical realist interpretation, such practices presuppose that theoretical models progressively refine our understanding of independently existing structures.

From a broader metaphysical perspective, this conjunction of ontological realism and epistemic limitation carries theological significance. Within a Christian doctrine of creation, the world is both intelligible and contingent: structured in a way that invites inquiry, yet not exhaustively comprehensible (Polkinghorne 2000; Torrance 1981). The mesoscale exemplifies this dual feature by displaying genuine causal order while remaining resistant to complete predictive mastery. Epistemic limitation, in this context, does not undermine realism but reflects the layered depth of created reality.

9. Conclusion: a call to contemplation and action

The mesoscale exemplifies a scientific domain characterised by the complex interplay of interactions, contingency, and dynamical sensitivity to perturbations, features that also shape human existence. Limits of modelling and understanding at the mesoscale do not imply a distinct mode of being at this scale, but they offer a powerful analogy to the human condition at the edge of openness and fragility.

Christian theology does not claim to offer a complete explanatory account of the problem of evil or of the forms of fragility that are manifest in the natural world. Rather, it interprets fragility in light of the Incarnation and the Cross, where divine transcendence is understood not as opposed to creaturely limitation, but as entering fully into it within the historical reality of redemption in Christ. As St Paul writes, "where sin increased, grace abounded all the more" (Romans 5:20), pointing to the superabundance of grace amid human brokenness.

For scientists, philosophers, and theologians, the mesoscale thus represents a domain in which empirical inquiry and metaphysical reflection converge. The layered intelligibility of mesoscale condensed matter invites rigorous investigation while not being fully exhausted by single-scale reduction. In this respect, the dialogue between science and theology is not a negotiation of competing explanations but a coordination of distinct yet complementary forms of rational engagement with the same reality. As Pope Francis observes in *Laudato Si'* (§62), science and religion can engage in a mutually enriching dialogue that respects the integrity of both domains.

Acknowledgements

The support of the European Commission through the MSCA-NanoECoAL project (Grant Agreement No. 101105556) is gratefully acknowledged. Insightful discussions with Revd Professor David Wilkinson are gratefully acknowledged.

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