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Review

Representation and Structural Change in Physical Modelling

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Abstract

This paper examines how different physical modelling frameworks represent structural change and asks when the organisation through which physical interactions occur should itself form part of the model state. The literature spans classical continuum mechanics and internal-variable theories, configurational mechanics, phase-field and cohesive fracture, enriched and unfitted methods, nonlocal and particle descriptions, quasicontinuum strategies, adaptive and higher-order networks, graph-based learning, and discrete differential and combinatorial formulations. These approaches provide different mechanisms for accommodating evolving geometry, interfaces, interactions, and topology and therefore reveal that the central issue cannot be reduced to a continuum-discrete distinction. The comparison is organised around the objects that carry physical quantities, the relations that determine admissible interactions, the transformations included in the state evolution, and the information about history retained after structural change. From this review, a relational synthesis is developed in which physical entities, their attributed relations, and the quantities carried by both may enter the state of an evolving system. Four concepts are introduced to make this synthesis operational: accumulative and reorganisational change, representational closure, structural memory, and representational transition. A minimal event-map formulation is proposed to identify the requirements for transferring physical quantities, constitutive information, and history when structural carriers change. Fatigue, environment-assisted degradation, transport, plasticity, and fracture are used as comparative tests of representational adequacy. The resulting framework does not prescribe a universal modelling formalism. It provides criteria for determining when structural information can be reduced to effective fields and internal variables, when explicit organisation becomes consequential, and how relational and continuum descriptions might be connected in a controlled manner.

Keywords: structural change; representational foundations; continuum mechanics; relational modelling; structural memory; representational closure; cell complexes; combinatorial modelling; fracture; transport

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1. Introduction and Scope

Physical modelling requires a choice of what constitutes the state of a system and how that state is allowed to evolve. In continuum mechanics this choice is usually expressed through fields defined on a body or spatial domain, supplemented where necessary by constitutive variables, interfaces, discontinuity descriptions, or additional kinematic structures [1–3]. The resulting framework has extraordinary scope. It supports deformation,

transport, thermomechanical coupling, damage, fracture, moving boundaries, and strongly nonlinear material response. The success of these formulations makes it especially important to distinguish genuine limitations of a representational foundation from limitations of a particular constitutive model, calibration strategy, or numerical implementation [4,5].

A recurring difficulty arises when the phenomenon of interest changes the organisation through which subsequent behaviour occurs. Fatigue crack initiation creates new interfaces after a long history of distributed cyclic deformation. Fracture removes load-bearing interactions and redirects forces. Transport pathways may open, close, or change dimensional character. Defects, phase boundaries, and microstructural junctions can appear, disappear, or change their physical role. These processes can be represented in several ways. Contemporary approaches include phase-field and cohesive descriptions of fracture [6–8], enriched and unfitted finite-element methods [9,10], configurational mechanics [11,12], nonlocal and particle-based models [13,14], adaptive and higher-order networks [15–17], graph and topological learning [18–20], and discrete differential or combinatorial formulations [21–24]. The useful question is how these frameworks represent change, which structural information they retain, and when that choice becomes consequential for explanation or prediction.

This article is a critical narrative of that question across continuum, nonlocal, network, discrete, and combinatorial approaches. The comparison is organised around four representational features: the objects that carry physical quantities; the relations that determine admissible interactions; the transformations included in the state evolution; and the treatment of history when organisation changes. Literature selection is guided by these representational questions. Foundational references are retained where they establish the mathematical commitments of a framework, while the recent literature from 2023–2026 is used to characterise current developments and applications. The main scope is mechanics, materials, fracture, and transport, with network science and scientific modelling included where they clarify the representational issues.

The literature reveals a spectrum of modelling strategies. Classical continuum descriptions preserve a continuous carrier while enriching the state with fields and internal variables. Configurational mechanics assigns driving forces to changes of material configuration. Phase-field methods encode crack geometry through diffuse fields, while the extended finite element method (XFEM) represents discontinuities independently of the underlying finite-element mesh, and peridynamics permits nonlocal interactions to degrade or fail. Particle and quasicontinuum strategies introduce alternative descriptions of the physical carrier or change the level at which it is resolved. Adaptive networks and dynamic graph models place evolving relations explicitly in the state. Discrete Exterior Calculus (DEC) and Finite Element Exterior Calculus (FEEC) preserve differential structure on discrete complexes, whereas Combinatorial Mesh Calculus (CMC) treats a cell complex as a possible physical carrier rather than solely as an approximation mesh. These approaches overlap in capability, yet they make different commitments about what constitutes the state and what must be introduced through additional fields, geometrical sets, interaction rules, or numerical procedures.

The synthesis developed from this comparison is a *relational representational foundation* for systems whose organisation is itself a modelling target. A relational state contains physical entities, their attributed relations, and the quantities carried by them. The carrier can be continuous, discrete, or mixed. Continuum descriptions remain appropriate wherever unresolved organisation can be represented reliably through effective fields and constitutive variables. Explicit relational structure becomes relevant when future behaviour depends on the identities or interaction pathways that an effective state suppresses.

Four concepts are developed to make this synthesis operational. *Accumulative change* alters quantities while retaining the organisation relevant at the chosen scale; *reorganisational*

change alters that organisation. *Representational closure* asks whether the state space remains capable of representing the states produced by the relevant mechanisms. *Structural memory* denotes history retained in present organisation when that history affects future evolution. A *representational transition* is required when a modelling task needs a state description with different objects, relations, or admissible transformations. All four concepts are scale- and representation-dependent. The same physical process may appear accumulative at one scale and reorganisational at another.

The original contribution of the paper lies in analysing otherwise separate modelling traditions through this common state-space question and in converting that comparison into operational criteria. The objective is to determine what structural information each representation retains, what transformations it admits, and what evidence would justify a change of representational foundation.

The remainder of this paper proceeds from existing methods to this synthesis. Section 2 compares major representational strategies for structural change and identifies their respective strengths and commitments. Section 3 formulates the relational synthesis and clarifies its scale dependence. Section 4 develops representational closure, structural memory, event maps, and transition criteria. Section 5 uses fatigue, transport, plasticity, and fracture as comparative tests. Section 6 distils criteria for evaluating representations and identifies a research programme for relational-continuum coupling. Section 7 summarises the conclusions.

2. How Existing Frameworks Represent Structural Change

2.1. Continuum Fields, Material and Spatial Descriptions, and Internal Variables

Classical continuum mechanics represents a body through a continuous material manifold and its configurations in physical space. A material description labels material points by a reference configuration and follows their motion, whereas a spatial description expresses fields at current spatial positions [2,25]. Both descriptions accommodate large deformation; changing shape or large strain does not by itself constitute a change of representational foundation. The relevant distinction for the present paper concerns the identity and organisation of the carriers on which the fields are defined.

Local balance laws and constitutive equations provide an economical description when the required state can be expressed through fields and suitable history variables. The Coleman–Noll procedure and related continuum-thermodynamic constructions constrain constitutive response by balance laws and the entropy inequality once a class of state variables has been selected [25,26]. Internal-variable theories then allow irreversible history dependence, hardening, damage, ageing, and other path-dependent effects to be represented without retaining the full trajectory of the material [27]. A potentially vast history can thereby be reduced to a state of manageable dimension.

The representational question considered here precedes constitutive admissibility. Given a selected state space, Coleman–Noll reasoning asks which constitutive maps are thermodynamically permissible. The present question asks whether the selected state space contains the objects and transformations needed to express the mechanism at the scale of interest. These questions are complementary. A richer state description remains subject to balance and thermodynamic restrictions, while constitutive admissibility alone does not determine whether the chosen state variables retain every distinction relevant to a particular target phenomenon.

Continuum formulations also admit singular sets, internal surfaces, evolving geometries, and mixed-dimensional structures. Statements that continuum modelling requires global smoothness or immutable geometry are therefore too broad. The meaningful comparison lies in how structural features are introduced and evolved: as fields on a carrier,

as explicit geometrical sets, as additional manifolds or interfaces, or as changes in the carrier itself.

2.2. Configurational Mechanics, Phase Fields, Cohesive Interfaces, and Enriched or Unfitted Methods

Configurational mechanics provides a direct continuum treatment of changes in material configuration. Material or configurational forces quantify the tendency of defects, cracks, phase boundaries, and inhomogeneities to move or evolve [11,12]. Recent finite-strain work demonstrates the continuing relevance of configurational forces for fracture assessment in soft solids [12]. This literature is important for the present discussion because continuum mechanics already contains a sophisticated language for structural evolution. Its focus is the driving force associated with changes of material configuration, with the material manifold and kinematic setting retained as part of the continuum formulation.

Phase-field fracture provides another powerful strategy. A sharp crack is regularised by a continuous damage or phase field, allowing nucleation, propagation, branching, and coalescence to occur without explicit tracking of the crack surface [6,28,29]. Contemporary formulations incorporate cohesive behaviour, finite deformation, fatigue, and coupled hydrogen transport [7,30]. Changes of crack topology can consequently emerge from the evolution of fields on the underlying domain. The crack is represented implicitly through the phase field.

Cohesive-zone models place constitutive traction-separation relations on interfaces. Depending on the formulation, interfaces may be predefined or activated dynamically as fracture develops [8]. XFEM and related enriched finite-element approaches permit discontinuities to cut through elements independently of the mesh, thereby reducing dependence on remeshing during crack propagation; recent reviews document extensive use in fatigue and fracture [9]. Unfitted and space–time methods similarly allow field problems to be solved on moving geometries without maintaining a body-fitted mesh at every step [10].

These approaches demonstrate substantial representational flexibility. Their distinction from the relational synthesis developed later concerns the state objects through which structural evolution is expressed. Phase fields encode a structural event through changes in field values. XFEM supplements the approximation with an explicit discontinuity description. Cohesive models introduce interface states and constitutive laws. Configurational mechanics supplies material forces for defect evolution. A relational representation asks whether the interface, pathway, junction, or other carrier should itself possess a persistent identity in the state and whether modification of its relations should be a directly admissible operation. Such explicit identity is useful when the history and subsequent role of individual structural constituents matters. Effective field descriptions remain preferable when those distinctions do not influence the modelling target.

2.3. Nonlocal Continua, Meshfree and Particle Methods, and Quasicontinuum Strategies

Nonlocal continua provide another route around difficulties associated with local differential descriptions of fracture and strong heterogeneity. Peridynamics replaces local stress-divergence equations by integral interactions over finite neighbourhoods. In bond-based and state-based formulations, damage can be represented through degradation or failure of interactions between material points, allowing cracks to emerge without a classical crack-tip singularity [13]. The framework is relational in an important operational sense because interactions between material points are explicit and may fail. It remains a continuum theory in which those points and their nonlocal neighbourhoods represent the material carrier. Recent reviews document developments across fracture, fatigue, multiphysics, multiscale modelling, and machine learning [13].

Meshfree and particle methods similarly reduce dependence on a fixed element topology. Smoothed-particle, element-free, lattice-particle, and related approaches represent continua through particles or interpolation neighbourhoods and can accommodate severe deformation, free surfaces, and crack evolution [14]. Their representational status depends on the purpose assigned to the particles. In many formulations they are numerical carriers approximating a continuum field problem. In others, particle or bond identity may be given physical meaning. The use of particles therefore leaves open the key representational question: whether those particles and their interactions correspond to physical entities and admissible transformations at the modelling scale.

Quasicontinuum methods make scale dependence particularly explicit. The original formulation couples atomistic resolution near defects to coarse-grained continuum-like regions, allowing the representation to adapt spatially to the local need for detail [31]. Quasicontinuum strategies provide an important precedent for representational transitions because different descriptions coexist within one computation and mappings between fine and coarse states are controlled systematically. Their principal target is multiscale resolution between atomistic and continuum descriptions. The question considered here extends this logic to organisation: a transition may arise because a different class of structural objects or transformations has become relevant, even when spatial resolution is already adequate.

2.4. Adaptive Networks, Higher-Order Relations, and Graph-Based Learning

Network science places relational structure at the centre of description. Adaptive networks couple node or edge states to changes in connectivity so that dynamics on the network and dynamics of the network co-evolve [15,32]. Higher-order network models extend this idea beyond pairwise edges to simplices, hyperedges, and other multiway interactions [16,17,33]. These frameworks establish the evolving interaction structure as a legitimate dynamical variable.

Network reorganisation and continuum structural evolution are nevertheless different modelling constructions. In an adaptive network, nodes and edges are primitive state objects and rewiring is an explicit dynamical operation. A continuum description generally represents material organisation through fields, interfaces, neighbourhoods, or other geometric and constitutive structures. Networks are therefore informative comparators rather than direct substitutes for continuum mechanics.

Physical networks add a further qualification. Abstract adjacency does not capture all information that matters when edges and nodes occupy space, have finite extent, obey geometrical constraints, or carry material attributes. Recent studies show that such physicality influences network formation and dynamics and can require network-of-networks or other enriched descriptions [34,35]. Relational modelling must therefore include geometry, orientation, type, capacity, and constitutive attributes whenever these affect interaction.

Graph neural networks have brought related ideas into computational mechanics. Recent reviews document graph representations of meshes, particles, structures, fractures, and multiphysics systems, with GNNs used to predict displacement, stress, damage, and evolving response on irregular domains [18]. Relational inference can infer newly appearing interactions [36]. Topological deep learning extends graph learning to simplicial, cellular, and combinatorial complexes [19]; higher-order cells have recently been used to retain object, surface, and contact organisation in learned rigid-body dynamics [20].

These developments lie close to the relational foundation developed below, although their objectives are different. A graph or cell complex used for learning may represent physical organisation, numerical adjacency, or a mixture of both. Learned message passing requires additional structure when conservation, constitutive semantics, or transfer of physical quantities across topology changes must be guaranteed. Relational learning can, in

turn, infer effective interactions that a prescribed physical model may miss. A productive combination would use a physically interpretable relational state as the carrier and impose balance constraints while learning uncertain constitutive or event rules.

2.5. Discrete Differential Frameworks: DEC, FEEC, and CMC

Discrete differential formulations encode fields through cochains and differential operators through incidence-related algebra. Discrte Exterior Calculus (DEC) represents differential forms and exterior-calculus operations on discrete primal and dual complexes and has been used as a structure-preserving discretisation and as a direct discrete language for physical laws [21,37]. Finite Element Exterior Calculus (FEEC) develops finite-dimensional subcomplexes of the de Rham complex and provides analytical conditions for stable approximation of continuum partial differential equations [22,38]. Both demonstrate that algebraic topology can preserve conservation and differential structure under discretisation.

Combinatorial Mesh Calculus builds on Forman's combinatorial differential forms and gives the complex a particular modelling role [23,24,39]. Cells may correspond to physical constituents rather than solely to numerical elements. Physical quantities are assigned directly to cells and relations, and balance laws are formulated intrinsically on the complex. Cells of different dimensions can carry different physical roles: volumetric pores, fractures, and channels, for example, can be represented by three-, two-, and one-dimensional cells within one transport model [40]. Recent work derives strong, primal variational, and mixed variational transport formulations directly on combinatorial meshes and demonstrates microstructure-driven prediction of permeability and thermal conductivity [24,41].

The distinction of CMC from DEC and FEEC is representational rather than a claim of exclusive algebraic novelty. Cochains, incidence matrices, and structure-preserving operators are shared ideas. FEEC is primarily a theory of stable approximation of continuum differential problems. DEC spans structure-preserving discretisation and direct discrete formulations. CMC systematically interprets the complex and its differently dimensional cells as possible physical carriers. Current CMC formulations operate on fixed complexes. Creation, deletion, splitting, merging, and reconnection of cells have yet to be incorporated into a complete physical evolution theory. This limitation motivates the event-map construction discussed in Section 4.

2.6. Comparative Synthesis of the Reviewed Approaches

Table 1 compares the reviewed frameworks through the state-space questions relevant here. It is intended as a map of representational choices. Each framework was developed for different purposes, and several can express the same physical event through different mathematical objects.

Table 1. Representational treatment of structural change in selected modelling frameworks. The final column identifies the distinction relevant to the relational synthesis rather than a general limitation of the method.

Framework	Primary Carrier/State	Treatment of Structural Change	Relation to the Present Synthesis
Classical continuum with internal variables	Fields on a material or spatial continuum; history variables	Geometry and fields evolve; history is condensed into constitutive state variables.	Effective when relevant structural distinctions can be represented by fields and reduced state variables [26,27].
Configurational mechanics	Continuum fields and material/configurational forces	Defect or interface evolution is driven by material forces.	Makes evolution of material configuration explicit within a continuum material setting [11,12].

Table 1. *Cont.*

Framework	Primary Carrier/State	Treatment of Structural Change	Relation to the Present Synthesis
Phase field, cohesive zone, XFEM, and unfitted methods	Continuum fields supplemented by diffuse damage, interfaces, enrichment, or moving geometry	Cracks and interfaces evolve through fields, interface states, enrichments, or explicit geometry.	Represents complex structural change while retaining a continuum carrier; structural information enters through additional fields or sets [6,8–10].
Peridynamics and particle/meshfree methods	Material points or particles with nonlocal or interpolation neighbourhoods	Interactions or neighbourhood contributions may degrade, fail, or evolve.	Makes interactions explicit; particles may have physical or numerical meaning depending on the formulation [13,14].
Quasicontinuum	Coupled atomistic and coarse-grained regions	Resolution changes while fine and coarse descriptions remain linked.	Provides a precedent for controlled transitions between descriptions driven mainly by scale and resolution [31].
Adaptive/higher-order networks and GNNs	Nodes, edges, hyperedges, simplices, or learned relational structures	Connectivity and attributes may co-evolve or be inferred.	Represents changing relations directly; physical meaning and conservation require additional specification [15,17,18].
DEC and FEEC	Cochains and discrete differential complexes	Usually formulated on a prescribed complex; changes of the complex require additional treatment.	Preserves differential and topological structure in discrete formulations [21,22].
CMC	Physical quantities carried by cells of a combinatorial complex	Current formulations evolve quantities on fixed incidence; topology-changing event maps remain to be developed.	Treats cells of different dimensions as possible physical carriers and incidence as part of the physical representation [23,24,40].

The comparison suggests that the central modelling choice concerns the allocation of physical meaning among fields, carriers, interfaces, neighbourhoods, and relations. Several established approaches already make parts of organisation explicit. A relational foundation becomes useful when the identities and relations of those parts must persist as state information and must themselves be transformed by the governing description.

3. A Relational Synthesis of Physical State and Organisation

The reviewed literature motivates a structural description with three interdependent components: entities, relations, and physical quantities. Entities are the distinguishable constituents relevant at the selected scale. They may be grains, interfaces, pores, channels, particles, defects, junctions, structural members, or other physically meaningful units. Relations specify how these entities are organised and how interaction is permitted. They may encode incidence, adjacency, containment, compatibility, transport accessibility, mechanical coupling, orientation, or a higher-order association. Physical quantities are assigned to entities, relations, or higher-order arrangements according to their physical role.

A relational state can therefore be written schematically as

$$s = (\mathcal{K}, q, h), \tag{1}$$

where $\mathcal{K}$ denotes the attributed structural carrier, q denotes the physical quantities carried by its objects, and h denotes additional constitutive or historical information required by the model. The notation $\mathcal{K}$ is intentionally generic. It may be a graph, hypergraph, cell complex, mixed-dimensional structure, particle neighbourhood system, or a continuous object equipped with explicit relational data. The defining feature is the state role assigned to organisation; discreteness is optional.

The carrier must contain more information than bare connectivity whenever the physics requires it. Two structures with identical adjacency may differ in geometry, orientation, interface character, capacity, or constitutive behaviour and therefore exhibit different responses [34,35]. Geometrically similar states may likewise differ in admissible interactions because an interface has debonded, a channel has become blocked, or a contact has formed. The state description must retain whichever distinctions affect the target behaviour.

The definition is explicitly scale-dependent. A crack may be represented at structural scale by a phase field on a continuous body, at mesoscale by the creation or reclassification of interfaces, and at atomistic scale by the loss and rearrangement of interatomic interactions. Plastic flow may leave the topology of a macroscopic body unchanged while reorganising dislocation structures, slip-system activity, or defect networks at a finer scale. The classification of a process as structural therefore has meaning only after the modelling scale and the identities of the state objects have been specified.

This scale dependence prevents a false competition between relational and continuum descriptions. A continuum model is preferable when the organisation that it suppresses is irrelevant to the target observables or can be represented reliably through effective fields and constitutive variables. A relational description becomes informative when future response depends on distinctions among entities or interaction pathways that the effective state identifies as equivalent. The resulting modelling problem is one of state sufficiency.

Figure 1 summarises the distinction. Accumulative evolution changes quantities on an unchanged carrier. Reorganisational evolution changes the carrier or its attributed relations. A representational transition is required only when the current state space cannot express the resulting state with stable physical meaning. A phase-field model, for example, may remain representationally closed with respect to crack branching because its phase field admits that event; a lower-dimensional relational model may represent the same event by explicit modification of interface objects. The appropriate choice depends on the questions asked of the model.

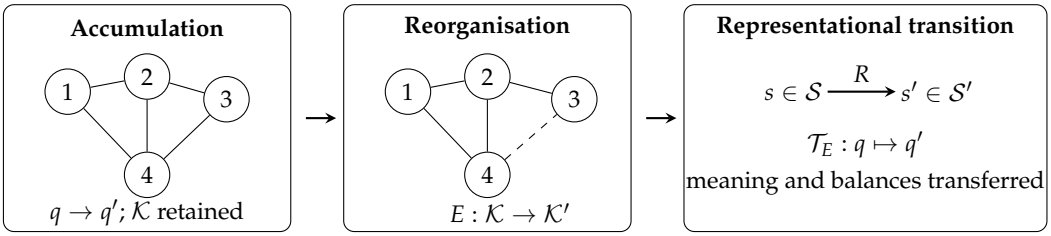


Figure 1. Conceptual distinction among accumulative change, reorganisational change, and a representational transition. Reorganisation can remain within one representation when its state space is closed with respect to the structural event.

4. Representational Closure, Structural Memory, and Event Maps

4.1. Accumulation, Reorganisation, and Representational Closure

For a chosen representation, let $\mathcal{S}$ denote the admissible state space and let $\mathcal{E}$ denote a class of physically relevant events. The representation is *representationally closed* with respect to $\mathcal{E}$ if every admissible event acting on an admissible state produces another state that remains expressible in $\mathcal{S}$ while the physical meanings of the state objects and quantities remain well defined. In schematic form,

$$e : \mathcal{S} \to \mathcal{S}, \qquad e \in \mathcal{E}. \tag{2}$$

This definition is relative to the modelling task. A phase-field state space may be closed with respect to crack nucleation and branching. A conventional elastic state space without damage or discontinuity variables lacks that capability. A cell-complex model on fixed

incidence is closed with respect to transport on that complex, while cell deletion requires an additional class of admissible events.

Within a relational state $s = (\mathcal{K}, q, h)$, *accumulative change* has the schematic form

$$(\mathcal{K}, q, h) \longrightarrow (\mathcal{K}, q', h'), \tag{3}$$

where the organisation represented by $\mathcal{K}$ is retained. *Reorganisational change* has the form

$$(\mathcal{K}, q, h) \longrightarrow (\mathcal{K}', q', h'), \qquad \mathcal{K}' \neq \mathcal{K}, \tag{4}$$

with respect to the structural distinctions retained at the selected scale. The distinction is mechanistic rather than numerical. A smooth auxiliary field may encode a physical reorganisation, while a discrete time update may approximate accumulation. The relevant question is whether the physical organisation controlling subsequent evolution has changed.

The scale qualification is essential. Macroscopic plastic strain can be accumulative in a conventional continuum description while dislocation reactions and evolving defect networks are reorganisational in a mesoscopic description. Fracture changes the topology of a body when a crack surface is represented explicitly; a diffuse phase-field formulation represents the same physical process through continuous evolution of its state fields. Representational closure must therefore always be stated relative to a scale, a state space, and a class of mechanisms.

4.2. Structural Memory as a Testable Property

Classical material memory is represented through internal variables, hereditary functionals, or other history-dependent state descriptions [26,42,43]. The relational synthesis introduces *structural memory* for cases where the present organisation carries information that affects future behaviour. The concept provides a test of whether a proposed reduction of history is sufficient.

Let $\Pi : \mathcal{S} \to \mathcal{R}$ denote a reduced description, for example, a set of continuum fields and internal variables. Consider two states $s_1, s_2 \in \mathcal{S}$ for which

$$\Pi(s_1) = \Pi(s_2). \tag{5}$$

If an admissible future loading L produces observably different responses,

$$\mathcal{F}_L(s_1) \neq \mathcal{F}_L(s_2), \tag{6}$$

then the reduction Π has removed state information relevant to that future response. When the distinguishing information resides in connectivity, interface state, pathway organisation, or another structural feature, the missing information is structural memory. This definition turns structural memory into a falsifiable property of a chosen reduced representation.

Candidate indicators are application-specific. Network connectivity, bottleneck statistics, interface-type distributions, percolating paths, loop or Betti-number information, and persistent-homology descriptors quantify different aspects of organisation. Recent work showing that network formation histories can be inferred from present topology illustrates that relational organisation can retain traces of past evolution [44]. In porous media, connectivity-bottleneck descriptors improve prediction of diffusive transport beyond simpler geometrical measures [45]. The useful indicator is the one whose retention restores equivalence between states with respect to the future responses of interest.

4.3. Event Maps and Conservation Across Structural Change

The feasibility of a relational theory of structural evolution depends on defining how physical quantities are transferred when the carrier changes. Let

$$E : \mathcal{K} \to \mathcal{K}' \tag{7}$$

represent a structural event such as interface opening, deletion of an interaction, splitting of a cell, creation of a contact, or reclassification of a relation. The structural map must be accompanied by a state-transfer map,

$$\mathcal{T}_E : \mathcal{X}(\mathcal{K}) \to \mathcal{X}(\mathcal{K}'), \qquad q' = \mathcal{T}_E(q), \tag{8}$$

where $\mathcal{X}(\mathcal{K})$ denotes the admissible physical quantities on the carrier. Historical or constitutive information may require a further transfer

$$h' = \mathcal{H}_E(h, q, \mathcal{K}, \mathcal{K}'). \tag{9}$$

Conservation constrains these maps. If $\mathcal{C}_{\mathcal{K}}(q)$ denotes a conserved extensive quantity, an event with external supply Q_E must satisfy a balance of the form

$$\mathcal{C}_{\mathcal{K}'}(q') = \mathcal{C}_{\mathcal{K}}(q) + Q_E. \tag{10}$$

The precise form depends on the physics. Mass, charge, energy, species content, and momentum require different transfer rules, while fracture and inelastic events additionally require an appropriate dissipation statement. Constitutive attributes assigned to an interface before rupture may need to be transformed into properties of newly created surfaces. Equations (7)–(10) identify the mathematical objects that a complete theory must provide. General event maps for CMC or other relational physical models remain an open development.

This formulation also clarifies the role of remeshing and other numerical operations. Remeshing can be a mathematically controlled part of a numerical method. The representational issue concerns whether the physical event and the associated transfer of quantities are governed by the model or supplied as an external reconstruction whose physical meaning lies outside the state evolution. Adaptive finite-element and quasicontinuum methods demonstrate that changing numerical carriers can be controlled systematically [10,31]. The relational programme requires analogous control for changes assigned direct physical meaning.

4.4. When Is a Representational Transition Required?

A *representational transition* is required when the target mechanism violates representational closure or when the state description loses distinctions needed for the future response of interest. The transition may involve enrichment of the current state, replacement of the carrier, activation of a complementary description, or a change in scale. This definition ties the decision to a specific failure of state sufficiency rather than to an arbitrary threshold in numerical error.

Four diagnostics make the criterion operational:

(i) **Event non-closure:** a physically relevant event cannot be represented as an admissible update of the existing state objects.

(ii) **State aliasing:** states identified as equivalent by the representation produce different future responses under the same admissible loading, as expressed by Equation (6).

(iii) **Semantic instability:** the meaning of a state variable changes after an event, so that the same mathematical quantity no longer denotes the same physical object or property.
(iv) **External structural intervention:** repeated insertion, deletion, reconnection, or reconstruction of model objects is required while these operations and their transfer rules are absent from the physical state evolution.

These diagnostics do not select a relational description automatically. The appropriate remedy may be an enriched continuum state, an evolving interface description, a nonlocal theory, a hybrid model, or an explicitly relational carrier. The latter becomes justified when the identities and relations of physical constituents must remain available for subsequent mechanisms or for the explanatory target of the model.

5. Applications as Comparative Epistemic Tests

Applications are used here to compare what different representations retain. Predictive disagreement can arise from missing physics, constitutive error, parameter uncertainty, numerical approximation, data limitations, or insufficient state description. A useful test asks whether models that reproduce similar macroscopic behaviour retain the same information about the mechanism and whether that information matters for subsequent evolution.

5.1. A Worked Conceptual Example: Fatigue Crack Initiation with Environmental Coupling

Fatigue crack initiation provides a useful worked example because a long period of distributed cyclic evolution precedes a local event that creates or activates a crack. Microstructure-sensitive fatigue models show that initiation depends on crystallographic orientation, grain neighbourhood, slip activity, local stress, and competing mechanisms [46–48]. Hydrogen-assisted fatigue adds transport, trapping, interface character, and chemical–mechanical coupling; recent work demonstrates sensitivity to grain size, anisotropy, misorientation, local plastic deformation, and hydrogen-affected boundary behaviour [49].

A contemporary phase-field description can couple cyclic degradation, hydrogen diffusion, and fracture resistance and can reproduce crack-growth trends over pressure, frequency, and load-ratio regimes [30]. In such a model the crack is represented by the evolution of a phase or damage field on a continuum domain. Crack nucleation and branching can occur within the same state-space construction. For predicting crack path or growth rate, this representation may be entirely adequate.

A relational description asks what additional state information is gained by retaining physical identity. Suppose grains are represented as volumetric entities, grain boundaries as interfaces, triple junctions as lower-dimensional entities, and transport or mechanical couplings as attributed relations. The pre-initiation state carries cyclic slip or stored energy in grains, hydrogen concentration and trapping data on the relevant carriers, and interface-specific strength or resistance. Accumulation changes these quantities while retaining the organisation. An initiation event E reclassifies or splits a bonded interface into a fractured state, removes or modifies the corresponding mechanical transfer relation, and may create new transport access to the crack surface. The transfer map $\mathcal{T}_E$ must preserve species content and the appropriate energy balance while changing the admissible flux and traction relations.

The comparison is informational. The phase-field model resolves an evolving fracture field efficiently and naturally. The relational model retains the identity of the particular interface that changed, its neighbouring entities, and the altered set of admissible interactions as explicit state information. The relational representation becomes useful if subsequent hydrogen transport, crack linkage, shielding, or branching depends on those identities in a way that a reduced field state does not preserve. The proposed test is to construct states

matched in conventional continuum observables and internal variables but differing in relational organisation, then determine whether their subsequent responses diverge. Such a study would directly test structural memory through Equation (6).

This worked example specifies the state, event, transfer, competing representations, and observable comparison needed for a future benchmark. Current CMC does not yet contain the event-map machinery required for this simulation, so the example is presented as a test design rather than as evidence of demonstrated superiority.

5.2. Transport and Emergence of Effective Properties

Transport offers a complementary test because the relation between structure and effective response can often be isolated more cleanly. In porous and fractured media, flow, diffusion, and heat transfer depend on connectivity, bottlenecks, tortuosity, interface properties, and the dimensional character of available pathways. Network descriptions have long exploited this dependence, and recent work shows that connectivity-bottleneck descriptors can materially improve prediction of diffusive transport [45].

CMC provides an existing example in which the complex is interpreted physically while its incidence remains fixed. Volumetric pores, sheet-like fractures, and narrow channels can be assigned to cells of different dimensions and coupled in a common conservation problem [40]. Permeability and thermal conductivity can then emerge from microstructure-specific calculations rather than being supplied as fitted macroscopic inputs [41]. These results demonstrate the first part of the proposed programme: explicit structural carriers can generate effective continuum properties in regimes where averaging is appropriate.

A natural epistemic test is to alter pathway organisation while controlling porosity and local transport properties. If two structures with similar conventional descriptors produce different effective responses because of bottlenecks or connectivity, a relational description can identify the source directly. If subsequent dissolution, clogging, fracture, or healing changes the pathways, event maps become necessary. The continuum description remains useful at scales where an updated effective coefficient faithfully represents the altered network.

5.3. Plasticity and Fracture: Different Roles of Reorganisation

Plasticity and fracture occupy different positions in this comparison. At the scale of a continuum body, conventional plastic deformation changes strain, stress, and internal state while preserving body topology. Internal-variable and crystal-plasticity formulations are therefore natural and successful descriptions. At finer scales, dislocation creation and reactions, junction formation, slip localisation, or transitions among defect organisations may constitute reorganisational change relative to the selected state objects. Recent combinatorial thermodynamic models interpret plastic flow in terms of transitions among organised deformation states [50,51]. Their relevance here lies in this scale-dependent reinterpretation; macroscopic plasticity itself need not change topology.

Fracture is a sharper structural example when crack surfaces or load-bearing relations are represented explicitly. Rupture removes or degrades interactions, creates surfaces, and redistributes load through the surviving organisation. Network fracture studies show that macroscopic fracture energy can depend systematically on strand mechanics and connectivity [52]; topology-informed studies similarly connect resistance to percolating or bridging structures [53]. Phase field, XFEM, peridynamics, cohesive models, and relational descriptions can all represent aspects of this evolution, while retaining different state information. Comparison becomes scientifically useful when crack arrest, branching, healing, transport access, or later loading depends on the specific surviving structure.

6. Criteria for Representational Adequacy and a Research Agenda

The reviewed frameworks show that predictive accuracy cannot by itself select a representational foundation. Several mathematically different descriptions can match the same observable within a calibration regime. Scientific understanding also depends on the justified relation between model objects, target features, and explanatory dependencies [54–58]. For evolving physical systems, four criteria condense the discussion above.

State sufficiency. The state should distinguish configurations whose future responses differ in ways relevant to the modelling target. This criterion permits substantial reduction when removed information is genuinely irrelevant. A reduction becomes insufficient when state aliasing is demonstrated by Equation (6).

Event closure. The representation should admit the physically relevant transformations within its state evolution. A phase-field model may satisfy this criterion for crack nucleation. A fixed-complex CMC model presently lacks closure with respect to cell deletion or reconnection. Closure is therefore assessed per mechanism and per representation.

Historical sufficiency. The state should retain the consequences of history needed for future response. Internal variables, hereditary functionals, structural descriptors, and explicit organisation provide different means of doing so. The appropriate choice is determined by whether states identified as equivalent remain equivalent under future admissible loading.

Transition fidelity. When a change of representation is used, the mapping between descriptions should specify which observables and balances are preserved, how quantities and history are transferred, and which structural information is discarded or reconstructed. Quasicontinuum coupling provides an established example of controlled fine–coarse transitions [31]. A relational–continuum transition requires analogous control over organisation and its associated physical quantities.

6.1. Trade-Offs and Domains Where a Relational Description Is Unnecessary

An explicit relational structure carries costs. Entity identification may be ambiguous, especially in disordered or continuously evolving media. The number of objects and event combinations can be large. Constitutive data may be required for interfaces and junctions that are difficult to characterise experimentally. Frequent topology changes can create algorithmic and data-management burdens. Coarse-graining and uncertainty quantification become more complicated when structural descriptors themselves are uncertain. These costs argue against retaining explicit organisation when its effect is adequately represented by continuum fields, effective coefficients, or a compact set of internal variables.

Continuum, phase-field, nonlocal, and enriched methods therefore remain preferable in broad classes of problems. A relational representation is justified by a specific gain: preservation of physically consequential identity, interaction structure, or history that would otherwise be lost. The comparison in Table 1 is intended to identify that gain rather than to promote a universal modelling hierarchy.

6.2. Research Priorities

This paper identifies five priorities for developing the relational synthesis into a testable modelling framework.

(i) **Event calculus:** Define admissible structural events $E : \mathcal{K} \to \mathcal{K}'$ and state-transfer maps $\mathcal{T}_E$ for creation, deletion, splitting, merging, contact, debonding, and reclassification of physical carriers.

(ii) **Balance and thermodynamic constraints:** Formulate conservation and dissipation conditions across events, extending the role played by balance laws and Coleman–Noll restrictions within fixed state spaces.

(iii) **Controlled reduction and reconstruction:** Develop coarse-graining maps from attributed relational states to effective continuum variables, quantify information loss, and determine when reconstruction of suppressed organisation is justified.

(iv) **Benchmark comparisons:** Construct paired tests in which continuum, phase-field, peridynamic, network, and combinatorial descriptions are calibrated to the same observables and then challenged by structural events or histories designed to expose state aliasing.

(v) **Learning on physical carriers:** Combine physically defined relational states with graph or topological learning to infer uncertain constitutive maps and event rules while preserving balance constraints and interpretable carrier identities [18–20].

For CMC specifically, the immediate mathematical task is concentrated in the first two priorities. Present formulations establish scalar conservation and variational transport on fixed cell complexes [23,24]. Extension to momentum balance, bundle-valued quantities, and topology-changing event maps would determine whether the framework can support the reorganisational programme proposed here. The required evidence is clear: conserved quantities must transfer consistently across structural events, the resulting state must remain physically interpretable, and comparisons with established models must establish when the additional structural information changes explanation or prediction.

7. Concluding Remarks

This paper has compared how major modelling frameworks represent structural change without reducing the comparison to a continuum-discrete opposition. Continuum mechanics accommodates large deformation, evolving interfaces, discontinuities, and defect motion through material and spatial descriptions, internal variables, configurational forces, phase fields, cohesive interfaces, enrichment, and moving-domain methods. Nonlocal and particle formulations make neighbourhood interactions more explicit. Quasicontinuum methods couple descriptions across scale. Adaptive networks and graph-based models allow connectivity to evolve. DEC and FEEC preserve discrete differential structure, while CMC assigns direct physical meaning to cells and their incidence relations. The literature therefore provides many complementary ways of describing evolving organisation.

The relational synthesis developed here identifies a common question beneath these approaches: which objects and relations must remain part of the state for the target mechanisms to be expressed and for future response to be determined? From this question follows the distinctions between accumulative and reorganisational change, the criterion of representational closure, the operational definition of structural memory, and the requirement for event and transfer maps when carriers change.

These concepts provide tests for when an explicit organisation adds information that an effective description suppresses. If two states that are identical in a reduced description remain equivalent under all relevant future loading, the reduction is adequate for that target. If they diverge because of retained differences in pathways, interfaces, or other organisation, the missing distinction becomes a candidate state variable. A representational transition is justified when the existing state space cannot incorporate that distinction or the events that create it while preserving physical meaning.

The immediate scientific opportunity is comparative. Existing methods should serve as benchmarks. Phase-field and XFEM provide mature descriptions of evolving cracks; configurational mechanics supplies driving forces for defect evolution; peridynamics and particle methods make interactions explicit; quasicontinuum supplies principles for controlled changes of resolution; and network science and topological learning provide tools for evolving relations. A relational physical model must demonstrate what additional

explanatory or predictive capability follows from treating the carriers and their organisation as state objects.

For combinatorial modelling, this leads to a concrete programme: formulate structural event maps, impose conservation and dissipation across them, develop controlled relational–continuum reductions, and test structural-memory hypotheses in applications where organisation affects subsequent behaviour. Fatigue initiation, environmentally assisted fracture, transport through evolving pathways, and microstructural plasticity provide different tests of the same representational question. Success would consist in identifying conditions under which explicit organisation is necessary, conditions under which it can be safely averaged, and mathematically controlled mappings between those regimes.

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