Nested Systems and Hierarchical Organisation

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Abstract

This paper distinguishes three hierarchies involved in the organisation and description of nested systems. The assembly hierarchy, also called the ontological hierarchy, describes how assemblies become components of greater assemblies. The causal emergence hierarchy traces the new capabilities that arise along assembly pathways. An assembly becomes a system when its organisation gives rise to and maintains a new capability to produce or accept a transfer. The epistemic hierarchy describes how we group assemblies and capabilities for a particular explanatory purpose. Causal emergence and causal integration help us recognise levels of organisation, and a single epistemic level can encompass several levels of causal emergence.

Assembly pathways can diverge, converge or end. Configuration spaces and energy landscapes help explain which arrangements can persist and which transitions are accessible under given conditions. Further increases in complexity are one possible outcome. The paper concludes that principles of General Systems Theory must apply at every level of organisation under their stated conditions. Laws that depend on particular emergent capabilities can be used alongside those principles to explain the systems in which those capabilities occur.

1. Introduction

A system can be part of a larger system while retaining its own internal organisation. An electrical generator, for example, contains interacting components that enable it to deliver electrical energy. When incorporated into a pumping installation, the generator supplies energy to the motor that drives the pump. The installation as a whole can deliver water from a source to a destination. If our immediate concern is how long it will take to fill a tank, we can describe the installation in terms of its water delivery rate and leave most of its internal interactions implicit.

This example illustrates three senses in which we can speak of a *level*. The *assembly hierarchy,* also called the *ontological hierarchy*, concerns what is part of what. The *causal emergence hierarchy* concerns the new capabilities that arise along an assembly pathway. The *epistemic hierarchy* concerns how we group and simplify assemblies and capabilities for a particular explanatory purpose.

These hierarchies are related. Several stages of assembly may be needed before a new capability emerges, and a single assembly may support several emergent capabilities. As components become causally integrated, some of their outputs become internal

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transfers within the larger system. This helps explain why we can often describe the larger system in terms of what it does as a whole. A single epistemic level can therefore encompass several levels of causal emergence.

Assembly and Disassembly as Causal Processes (Challoner, 2026a) explains how assemblies form, persist and become components of larger assemblies. *A Causal Account of Emergence* (Challoner, 2026b) explains how new capabilities arise through causal organisation. This paper brings those accounts together to examine how systems are organised across levels. It considers why assembly pathways diverge, converge or end, and how configuration spaces and energy landscapes help explain which arrangements persist and which transitions are possible under given conditions. It then considers what belongs in a general theory of systems and how general principles can be used alongside laws that apply to particular kinds of system.

2. The Assembly Hierarchy

The *assembly hierarchy*, also called the *ontological hierarchy*, describes the part–whole relationships that arise when assemblies become components of greater assemblies (Simon, 1962). This can happen repeatedly. An assembly may retain much of its internal organisation when incorporated into a greater assembly. It is then a *sub-assembly* of that greater assembly, which we can also call its *super-assembly*. These terms describe a hierarchical relationship; the same assembly can contain sub-assemblies and itself be a sub-assembly of a greater whole.

In a pumping installation, the generator contains a rotor, a stator and other components arranged so that it can deliver electrical energy when driven. When incorporated into the installation, it retains this capability and supplies electrical energy to the motor. The motor transfers mechanical energy to the pump, which acts on the water. The generator is an assembly in its own right and a sub-assembly of the installation. The electrical transfer crosses the generator's boundary and takes place within the installation.

To establish a part–whole relationship, we look at how an entity is incorporated into the greater assembly. A spare generator stored beside the pump may be available for future use. The installed generator participates in the organisation of the pumping installation through its connections and its role in supplying power. That relationship can persist while the generator is switched off. The connections and organisation needed to resume operation are still in place.

An assembly hierarchy can branch. The generator and the motor-driven pump each have their own internal organisation. Both are sub-assemblies of the pumping installation, which can in turn become a sub-assembly of a wider water supply network. A description of the hierarchy therefore depends on which assembly we start with and which part–whole relationships we follow.

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Each step in the assembly hierarchy identifies a further level of part–whole organisation.

The next section examines when such a step gives rise to a new causal capability and how emergence distinguishes a system from the wider class of assemblies.

3. The Causal Emergence Hierarchy

Emergence is what distinguishes a *system* from the wider class of assemblies. In the sense developed in *A Causal Account of Emergence* (Challoner, 2026b), an assembly becomes a system when its organisation gives rise to and maintains a new capability to produce or accept a transfer. The novelty can lie in how the transfer takes place or in the causal role it plays. An organised assembly that does not sustain an emergent causal capability is called a *pre-systemic assembly*. It may already have an organised structure and may contribute to a capability that emerges at a later stage.

Consider the pumping installation. The generator can deliver electrical energy when driven, and the motor-driven pump can transfer energy to water. When these assemblies are connected to suitable pipework, the installation as a whole can deliver water from a particular source to a particular destination. The water itself may be unchanged. What emerges is the installation's capability to transfer it between those locations. That capability remains available while the installation is switched off, provided the organisation needed to resume operation is maintained.

Systems also form a hierarchy founded on the assembly hierarchy. A system that forms part of a greater system is a *sub-system* of that greater system, which is its *super-system*. In this example, the generator is a system in its own right and a sub-system of the pumping installation. The installation is the generator's super-system and may in turn be a sub-system of a wider water supply system.

Each new emergent capability establishes a *causal level* relative to the assembly pathway through which it arose. Several stages of assembly may be needed before a new capability emerges, and a single assembly may support several emergent capabilities. A causal hierarchy therefore follows the capabilities that arise along an assembly pathway, while the assembly hierarchy follows the part–whole relationships formed along it. The next section considers how we group these assemblies and capabilities into levels of description.

4. The Epistemic Hierarchy

An *epistemic hierarchy* is an arrangement of levels of description. At each level, we group and simplify what we know about assemblies and their capabilities so that we can answer a particular question. This is a form of *epistemic compression*. A single epistemic level can encompass several levels of causal emergence. Craver (2007) likewise distinguishes levels of mechanisms from levels of science and levels of theory.

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For example, if we want to estimate how long it will take to fill a tank, we can treat the pumping installation as a unit. Given the volume required and the delivery rate, we can estimate the filling time. This description leaves electrical generation, the transfer of mechanical energy and the action of the pump on the water implicit. If the delivery rate falls unexpectedly, we may need to examine those processes separately to find where the change arose. The installation is the same in both cases. The question determines how much of its causal organisation we need to describe.

Emergence and causal integration both help explain why we recognise particular epistemic levels and treat certain entities as units of description at those levels. Emergence establishes new capabilities to produce or accept transfers. These capabilities give us a reason to describe the organised whole as a source or recipient in its own right. Through causal integration, transfers between components can become internal to the system, and exchanges between components and the wider environment can be mediated by other parts of the system.

A free-living cell can take up nutrients from its surroundings. In a mammal, many cells take up nutrients from the fluid around them after the circulatory system has delivered those nutrients to their tissues. The transfer into each cell still takes place, but the route by which nutrients reach the cell now depends on the organisation of the mammal. When explaining how the mammal obtains and distributes nutrients, we can describe it as a whole and leave many of those internal transfers implicit. The epistemic level is chosen for the explanation, and the organisation of the system helps make that description possible.

The capability to deliver water to the tank gives us a reason to describe the installation as a whole. Causal integration makes that description practical. The generator's electrical output becomes an internal transfer to the motor, and the motor transfers mechanical energy to the pump. We can describe the resulting water delivery at the boundary of the installation while leaving those internal transfers implicit.

The scientific disciplines illustrate epistemic hierarchies on a wider scale. Subatomic physics, other branches of physics, chemistry, biochemistry, biology and the social sciences focus on different kinds of organisation and capability. A biologist may describe a cell as a unit that takes up nutrients and responds to signals. A biochemical explanation can examine the processes within the same cell that make those capabilities possible. The disciplines overlap, and fields such as information theory and epistemic theory address questions that cut across several levels.

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Hierarchy	What it describes	Pumping installation example
Assembly	Part–whole relationships	The generator is a sub-assembly of the pumping installation.
Causal Emergence	New capabilities that arise along an assembly pathway	The connected installation can deliver water from a particular source to a particular destination.
Epistemic	How we group assemblies and capabilities for a particular explanation	We use the installation's delivery rate to estimate filling time, leaving electrical generation and pumping implicit.

Figure 1 illustrates how a single epistemic level can encompass several levels of causal emergence along branching assembly pathways.

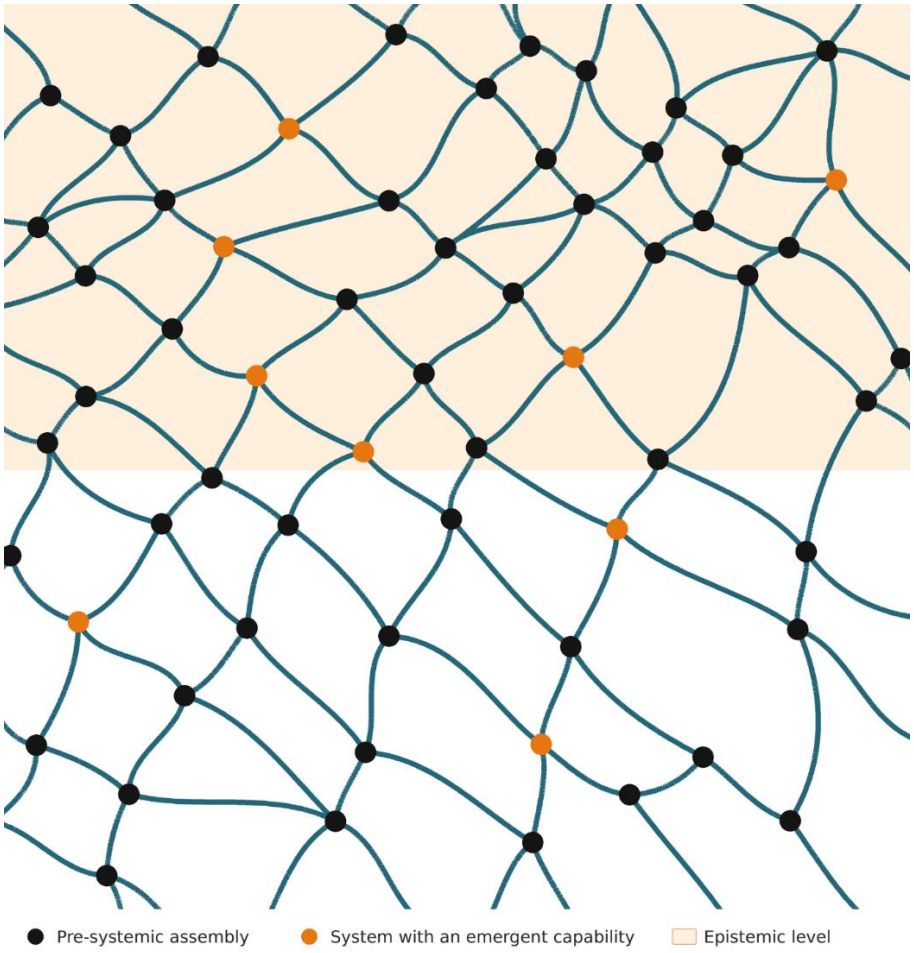

Figure 1. *Simplified schematic diagram illustrating the relationship between assembly hierarchies, causal emergence hierarchies, and epistemic hierarchies. The blue lines indicate assembly pathways.*

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5. Assembly Pathways and Their Outcomes

An *assembly pathway* is a sequence of interactions through which an assembly forms. At any stage, an assembly may persist, change its arrangement, join another assembly or break apart. What happens next depends on its existing organisation, what it encounters and the conditions under which the interaction takes place.

Pathways *diverge* when the same starting assembly can take different routes. For example, a pair of bound particles may encounter different partners and become part of different assemblies. Pathways *converge* when different sequences lead to equivalent assemblies, or when assemblies formed along separate routes become components of a greater assembly. The generator and the motor-driven pump, for example, can be assembled separately before being incorporated into the same pumping installation. A single part–whole diagram of the finished installation can therefore correspond to several possible assembly histories.

5.1 Configuration Spaces and Energy Landscapes

A *configuration space* represents the possible arrangements of the components. Each point corresponds to one arrangement, and a pathway through the space traces the changes from one arrangement to another. An *energy landscape* represents how potential energy varies across those arrangements (Wales, 2003). Its low regions help explain where assemblies can persist, while barriers help explain why some changes are difficult under given conditions. Whether a transition occurs also depends on how the components are moving and what energy they can gain or lose through interactions.

When two particles bind, the bond constrains their motion relative to one another. The pair can then interact with another particle as a unit. If the pair retains its organisation when incorporated into a greater assembly, a further step in the *assembly hierarchy* has occurred. If the resulting organisation gives rise to and maintains a new capability to produce or accept a transfer, a new level of *causal emergence* has arisen. We can also describe the bound pair as a unit when its internal motions make little difference to the question at hand. That is a form of *epistemic compression*.

5.2 Persistence and Further Assembly

The conditions that favour persistence can also limit further assembly. A tightly bound cluster may hold together for a long time, yet be difficult to rearrange when another component approaches. A cluster whose components can shift while remaining bound may be able to incorporate that component. Some branches therefore go no further under the prevailing conditions even though their assemblies persist. Others end when assemblies break apart or when the partners or conditions needed for a further step are absent.

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In biological evolution, a lineage can end when its organisms cease to leave descendants. Whether it continues depends in part on how inherited capabilities affect survival and reproduction in the prevailing environment. A capability that once favoured reproduction may become costly when conditions change, and losing it may then be advantageous. Some populations of the Mexican tetra, for example, have lost functional vision over generations. This illustrates how a lineage can persist while losing a capability. In dark, food-limited caves, the energy saved by reducing the visual system may have contributed to that loss (Moran et al., 2015). A lineage can therefore persist with much the same organisation, become simpler or develop further levels of assembly. Which outcome occurs depends on the changes that are accessible and on their consequences under the conditions the lineage encounters. There is no general evolutionary requirement for lineages to increase in complexity (Szathmáry & Maynard Smith, 1995).

6. Implications for General Systems Theory

Von Bertalanffy (1968) sought principles applicable to systems generally. The principles of General Systems Theory must be applicable to systems at every level of organisation under their stated conditions. A general principle can explain how the organisation of components gives rise to a new capability. The particular laws and regularities that depend on that capability belong to the theory of the systems in which it occurs. For example, GST can explain how a generator, motor, pump and pipework jointly make water delivery possible. To calculate the delivery rate, we also need the characteristics of the pump and the hydraulic conditions in the pipework.

The three hierarchies help us choose the level of detail an explanation requires. To estimate how long a tank will take to fill, the delivery rate may be sufficient. To explain why the rate has fallen, we may need to trace the transfers among the components or examine changes in the conditions under which the installation operates. An epistemic compression is useful when it retains the relationships that matter for the question. When we need more detail, we can use the assembly hierarchy to locate the relevant components and the causal emergence hierarchy to identify the capabilities on which the outcome depends.

A general theory must also accommodate the different routes by which systems form and the different outcomes of those routes. Assembly pathways can diverge, converge or end. Assemblies can persist at much the same level of organisation, be incorporated into greater assemblies or break apart. The explanation in each case depends on the interactions that are possible, the conditions under which they occur and the organisation they establish or disrupt.

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7. Summary and Conclusions

Nested organisation can be understood through three related hierarchies. The *assembly hierarchy*, also called the *ontological hierarchy*, records how assemblies become parts of greater assemblies. The *causal emergence hierarchy* follows the new capabilities that arise and are maintained along assembly pathways. Such a capability distinguishes a system from a pre-systemic assembly. The *epistemic hierarchy* reflects how we group and simplify assemblies and their capabilities for a particular purpose.

Several stages of assembly may precede the emergence of a new capability, and a single assembly may support several emergent capabilities. Emergence gives us a reason to describe an assembly in terms of what it can do as a whole. Causal integration helps make that description possible by allowing us to leave internal transfers implicit. A single epistemic level can thus encompass several levels of causal emergence.

Assembly pathways can diverge, converge or end. Configuration spaces represent the arrangements available to the components, and energy landscapes help explain which arrangements can persist and which transitions are accessible under given conditions. The conditions that sustain an assembly can also limit its incorporation into a greater assembly. Persistence is therefore compatible with little change in complexity, and disassembly can reduce it.

For General Systems Theory, the distinction between the three hierarchies clarifies both the scope of the theory and how to apply it. General principles must be applicable at every level of organisation under their stated conditions. Laws that depend on particular emergent capabilities belong to the theories of the systems that possess them. In a particular investigation, the question determines the level of description, and the assembly and causal emergence hierarchies help us recover the relevant interactions and transfers when a more detailed explanation is needed.

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Definitions

D5.8 – Assembly (Updated)

An assembly is an organised entity resulting from, or subsequently modified through, causal assembly, whose organisation includes two or more entities as components.

D5.9 – Pre-Systemic Assembly (Updated)

A pre-systemic assembly is an organised assembly that does not sustain an emergent causal capability.

D5.10 – System (Updated)

A system is an organised assembly whose maintained organisation supports a capability to produce or accept transfers that its components do not possess acting separately.

D5.17 – Component (Updated)

An entity participating in the organisation of a more extensive entity is a component of that entity. Such participation may include physical retention and constraint and need not involve a contribution to the interactions constituting its focal organisation or function.

D5.18 – Sub-system

A system that forms part of a larger system.

D5.19 – Super-system

A system containing one or more sub-systems.

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D5.21 – Emergence (Updated)

Emergence occurs when the causal organisation of participating components establishes and maintains a capability to produce or accept physical transfers that those components cannot produce or accept independently. The capability may remain unrealised until suitable causal circumstances arise and may persist for as long as the organisation supporting it is sufficiently maintained.

D8.1 – Causal Integration

Causal integration is the reorganisation of causal relationships and transfers as previously separate entities become causally coupled within a more extensive assembly. It may alter how components exercise their existing capabilities without necessarily establishing a new emergent capability.

D8.2 – Transfer Internalisation

Transfer internalisation occurs when transfers previously occurring between independent entities become internal to a more extensive assembly, so that they no longer cross the boundary of that assembly.

D8.3 – Transfer Mediation

Transfer mediation occurs when transfers between a component and its wider environment take place through other components or processes of the containing assembly rather than directly.

D8.5 – Causal Level

A causal level is a distinction in physical causal capability established through emergence relative to the participating components and the assembly pathway through which that capability arises.

D8.6 – Organisational Level

An organisational level is a position within a nested arrangement of physical entities in which assemblies become components of more extensive assemblies. The establishment of an organisational level does not necessarily establish a new causal level.

D8.7 – Epistemic Level

An epistemic level is a classification of physical entities, organisations or capabilities established through epistemic representation and compression. Such levels may correspond to recurring features of causal reality, but their boundaries depend partly upon the purpose of the investigation.

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D4.4 – Compression

The simplification of information through the representation of recurring structures, patterns, or relationships in cognitively manageable form.

D4.5 – Causal Compression

The representation of recurring causal organisations in simplified conceptual form.

D9.1 – Assembly Hierarchy

An assembly hierarchy is the arrangement of part–whole relationships formed when assemblies become components of greater assemblies. In GST 09, this is also called the ontological hierarchy.

D9.2 – Sub-assembly

A sub-assembly is an assembly that participates as a component of a greater assembly.

D9.3 – Super-assembly

A super-assembly is a greater assembly considered in relation to an assembly that participates as one of its components.

D9.4 – Causal Emergence Hierarchy

A causal emergence hierarchy is the arrangement of causal levels established by emergent capabilities along one or more assembly pathways.

D9.5 – Epistemic Hierarchy

An epistemic hierarchy is an arrangement of levels of description in which assemblies and capabilities are grouped and represented at different degrees of detail for a particular purpose.

D9.6 – Assembly Pathway

An assembly pathway is a sequence of causal interactions through which an assembly forms, potentially through intermediate assemblies.

Note

Configuration space and energy landscape are introduced in Section 5.1 and treated in more detail in a future paper.

Propositions

P7.30 – Ontological Hierarchy Proposition (Hypothesis)

Recursive assembly may establish levels of physical organisation where assemblies become components of more extensive assemblies. Such nesting need not establish a

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new emergent capability at every stage. Where maintained organisation supports a capability unavailable to the components acting separately, a further distinction in emergent capability can be identified.

P8.4 – Causal Levels Proposition (Hypothesis)

Within an ontological hierarchy, successive levels of assembly do not necessarily establish new causal levels. A new causal level arises where the organisation of participating components establishes an emergent capability unavailable to those components acting independently. Causal levels are therefore relative to particular assembly pathways and need not form a single universal hierarchy.

P9.1 – Nested Systems Proposition

Where a system participates as a component of a greater system, their relationship is that of sub-system and super-system. Repeated incorporation can establish a hierarchy of nested systems within the assembly hierarchy.

P9.2 – Epistemic Levels Can Encompass Several Causal Levels

A single epistemic level may group assemblies and capabilities from several levels of causal emergence. Emergence can provide a reason to describe an assembly as a whole, and causal integration can make that description practical by allowing some internal transfers to remain implicit.

P9.3 – Divergence and Convergence of Assembly Pathways

An assembly pathway can diverge when a starting assembly encounters different partners or conditions. Pathways can converge when different sequences produce equivalent assemblies or when separately formed assemblies become components of the same greater assembly.

P9.4 – Persistence and Further Assembly Proposition

Conditions that sustain an existing assembly can limit further assembly where incorporation requires rearrangements that those conditions inhibit. An assembly can therefore persist even when its pathway goes no further under prevailing conditions.

P9.5 – Scope of General Systems Theory Proposition

A principle of General Systems Theory must apply to systems at every level of organisation under its stated conditions. Laws that depend on capabilities specific to particular kinds of system can be used alongside general principles to explain those systems.

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