A Causal Account of Emergence

John A Challoner, November, 2026

Abstract

Emergence occurs when the organisation of physical entities establishes capabilities that their participating components cannot exercise independently. Although emergence is widely recognised across scientific disciplines, explaining how such capabilities arise requires an understanding of the physical processes responsible.

Building upon the Causal Assembly Theory developed in an earlier paper, this paper proposes a general causal account of emergence based upon the organisation of physical interactions and transfers of matter, energy and physically embodied information. Emergent capabilities are understood as abilities to produce or accept transfers that the participating components cannot produce or accept independently. This approach distinguishes the physical reality of emergence from novelty arising merely through observation or changes in understanding. It also distinguishes between the existence of a capability and its realisation, allowing for transient, persistent and latent emergence.

A seven-step method is proposed for identifying and investigating emergent capabilities through their associated transfers, causal processes, participating components and organisational dependence. The paper also examines how causal integration can alter the expression of existing component capabilities, helping to explain so-called vanishing properties. It proposes that emergent capabilities establish causal levels relative to particular assembly pathways, while epistemic compression enables these numerous levels to be represented through broader classifications.

Finally, the paper explores how emergent capabilities may influence evolutionary change by altering the causal relationships and circumstances experienced by other assemblies. These developments suggest a common physical framework for investigating emergence across different domains. However, the general applicability of the proposed account, its interpretation of causal levels and its wider evolutionary implications remain hypotheses requiring further investigation and testing.

1. Introduction

The components of a system can become organised in ways that enable the system as a whole to do things that its components cannot do independently. For example, the components of an electric generator cannot independently convert mechanical energy

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into a controlled electrical output. That capability arises from their organisation and interaction. This phenomenon is known as *emergence*.

Emergence is important because it helps explain how increasingly varied capabilities can arise in physical reality without requiring new fundamental physical laws. However, describing a capability as emergent does not, by itself, explain how it arises. For that, we need to understand the physical processes responsible.

The previous paper in this series, *Causal Assembly Theory: Assembly and Disassembly as Causal Processes* (Challoner, 2026a), provides a foundation for such an explanation. It describes how physical entities become organised as components of larger assemblies, how that organisation is maintained or changed, and how it can eventually break down. It also explains how organised components participate in *causal processes*: connected physical interactions through which transfers occur.

A *transfer* is the movement or transmission of matter, energy or physically embodied information from a source to a recipient. Transfers may occur within an assembly or across its boundary, where they are commonly described as inputs and outputs (Challoner, 2026b).

The previous paper in this series proposed that a system is an organised assembly possessing a maintained *emergent causal capability*: an ability to produce or accept transfers that its components cannot produce or accept independently. This provides a physical basis for investigating emergence.

The present paper develops that account by examining how causal organisation establishes emergent capabilities and how those capabilities can be recognised and investigated. Particular attention is given to the processes responsible for producing and accepting transfers, including the physical patterns, i.e., information, that those transfers may carry.

The paper also considers several consequences of emergence. Emergent capabilities may be temporary or persist over time, and different causal processes may establish equivalent capabilities. Furthermore, emergence can establish new possibilities for causal relationships between physical entities. These possibilities are *ontological*, meaning that they concern what exists and can occur in physical reality, rather than merely in how we describe or understand it.

The paper also considers what happens to the capabilities of components when they become part of a larger assembly. Some may operate primarily within the assembly, thus becoming less apparent externally, while others may be constrained or prevented from operating. These changes can help explain why we recognise some assemblies as distinct entities with their own capabilities more readily than others. The implications of this for our understanding of different levels of physical reality are also explored.

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Finally, the paper explores a possible connection between emergence and evolution. Outputs made possible by emergence can alter the circumstances experienced by other systems. In some cases, they may support the persistence or proliferation of those systems, either directly or through networks of interacting systems. Such changes may, in turn, create opportunities for further emergence.

The aim is to develop a general causal account of emergence that can be investigated and tested across different domains. The account is intended to explain emergence through established physical interactions and the organisation of causal processes, while identifying those wider propositions that remain hypotheses and require further investigation.

2. Causal Processes and Emergent Capabilities

2.1 From Components to Causal Processes

Every physical entity possesses capabilities to interact with other entities under suitable circumstances. These capabilities depend upon its physical properties and organisation.

As explained in the previous paper in this series, assembly occurs when previously separate entities become organised as components of a more extensive entity. Physical interactions and constraints establish and maintain relationships between the components (Challoner, 2026a).

These relationships can enable *causal processes*, which are sets of connected physical interactions through which transfers occur. A process may involve a sequence of interactions, several interactions converging on a common outcome, branching pathways, or recurring cycles.

For example, an electric generator contains components that interact mechanically, magnetically and electrically. Their organisation enables a process in which mechanical rotation produces an electrical output.

This process depends upon the components and their interactions, but it also depends upon how those components are organised. Changing their arrangement or connections may prevent the process from operating, even though the individual components remain intact.

Thus, assembly can establish causal processes that would not otherwise be possible.

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2.2 From Causal Processes to Emergent Capabilities

Some causal processes enable an assembly to produce or accept transfers that its components cannot produce or accept independently. The ability to do so is an *emergent causal capability*.

The generator's components possess individual mechanical, magnetic and electrical capabilities. However, their organisation enables the generator to accept mechanical energy and produce a controlled electrical output.

This emergent capability depends upon the relationships between the components. If those relationships are disrupted, the generator may lose its ability to produce the output, even though its components retain their individual capabilities.

An emergent capability is therefore not an additional physical substance or force. It arises from the organisation of existing physical entities and their interactions.

It is also important to distinguish a *capability* from its *realisation*. A capability is the ability to produce or accept a transfer under suitable circumstances. Its realisation occurs when the relevant causal process operates and the transfer takes place. Consequently, the generator retains its capability to produce electricity even when it is stationary. Thus, an emergent capability need not be continuously exercised to exist.

2.3 Systems and Pre-Systemic Assemblies

The previous paper distinguished between *systems* and *pre-systemic assemblies* according to their causal capabilities. A *system* is an organised assembly possessing a maintained capability to produce or accept transfers that its components cannot produce or accept independently. A *pre-systemic assembly*, on the other hand, possesses organisation, accepts inputs and delivers outputs, but lacks a maintained emergent causal capability.

This distinction is important because assembly does not necessarily establish emergence. For example, consider a group of people who communicate with one another to avoid interfering with their separate activities. Each person receives information from others, adjusts their own behaviour and continues pursuing their individual purposes. Their interactions establish some organisation, but they do not necessarily establish a collective capability.

The question we need to ask, therefore, is whether the assembly as a whole has acquired a capability to produce or accept transfers that its members cannot produce or accept independently. If the answer is no, the group remains a pre-systemic assembly. If the organisation establishes such a capability and maintains it, the group qualifies as a system.

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The distinction does not depend upon whether the people share a common purpose. Even unintended coordination may establish an emergent capability. What matters is whether the organisation enables the assembly as a whole to do something that its members cannot do independently.

An assembly may also support several causal processes, some of which establish emergent capabilities and others of which do not. These processes may share components, and changes in one process may affect the operation of another.

2.4 The Role of Organisation

The preceding examples suggest that the key to understanding emergence lies in the causal organisation of the participating components. This organisation includes their physical configuration, the interactions between them, and the constraints that enable or inhibit particular stages of a causal process.

A *constraint* is a causal influence arising from elsewhere in an assembly or its environment that enables, inhibits or limits a particular stage of a causal process.

For example, the bearings of our generator constrain the movement of its rotating components, allowing rotation about a particular axis while inhibiting other movements. Electrical connections provide pathways through which current can flow. The arrangement of magnetic and conducting components enables electromagnetic interactions to produce the intended output. These relationships do not introduce new fundamental physical laws. Instead, they establish circumstances in which existing physical interactions can produce outcomes that the components cannot produce independently.

Organisation can therefore both enable and constrain causal processes. An emergent capability exists when the resulting organisation establishes an ability to produce or accept transfers that is unavailable to the components acting separately.

2.5 Section Summary

In summary, therefore:

- Assembly establishes organised relationships between physical entities. These relationships can enable causal processes through which transfers are produced or accepted.
- Where the organisation establishes a capability unavailable to the participating components independently, that capability is emergent.
- Not every assembly possesses such a capability, and a capability need not be continuously realised to exist.

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The next section examines the transfers themselves, including how their physical organisation and the patterns they carry can help us understand what is novel about an emergent capability.

3. Emergence and Physical Transfers

3.1 The Nature of Physical Transfers

As explained in *Foundational Causality* (Challoner, 2026b), causal relationships involve transfers of matter, energy or physically embodied information between a source and a recipient.

A transfer may involve an individual physical entity, an assembly, or a collection of assemblies. The transferred entities may themselves possess internal organisation. For example, a parcel delivered from one business to another is the transfer of an assembled physical entity. Its contents may include several smaller assemblies, each possessing its own causal capabilities.

Transfers may also involve energy without the movement of a complete material assembly from source to recipient, as occurs when electromagnetic radiation is emitted and subsequently absorbed.

The physical organisation underlying a transfer can be examined at different levels of detail. A transfer that is treated as a single event at one level may involve numerous connected causal interactions when examined more closely.

However, this does not imply that every transfer must possess an underlying network of simpler interactions. Some transfers at the fundamental physical level may not be further decomposable.

The same principle applies to the source and recipient entities. Each may be treated as a whole for a particular investigation or examined in greater causal detail where necessary.

3.2 What Makes an Output Emergent?

An emergent output does not necessarily involve a new form of matter or energy. Rather, its novelty may lie in the physical organisation of the transfer, the pattern it carries, or the circumstances under which the assembly becomes capable of producing it.

Consider the electric generator introduced in Section 2. The generator accepts mechanical energy and produces an electrical output. Neither mechanical nor electrical energy is novel. However, the organisation of the generator's components establishes a capability to produce an electrical output from a mechanical input that those components do not possess independently. The novelty therefore lies in the

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organised causal capability and the output it makes possible, rather than in the existence of electrical energy itself.

The distinction is important because an emergent output need not be unprecedented in physical reality. Another assembly, operating through a different process, may produce an equivalent output. What matters is whether the organisation of the assembly under investigation establishes a capability unavailable to its participating components acting separately.

3.3 What Makes an Input Emergent?

Emergence can also concern an assembly's capability to accept a transfer. In this case, novelty may lie in the way the assembly receives, distinguishes or responds to an incoming transfer.

For example, consider a simple light-sensitive organism. Its light-sensitive molecules interact with incoming electromagnetic radiation. However, their organisation with other components may enable the organism to detect illumination and produce a corresponding response. The emergent capability is not simply the absorption of light by individual molecules. It is the organised capability to accept the incoming transfer and produce a response that the components cannot produce independently.

More elaborate arrangements may enable an organism to distinguish the direction of incoming light or differences in illumination across its surroundings. These additional capabilities depend upon further causal organisation.

Thus, emergence concerns the novelty of the outputs or inputs associated with a causal capability, not necessarily the novelty of the physical substance or energy being transferred.

3.4 Emergence and Information Transfers

Information transfers provide a particularly useful illustration of how novelty can depend upon physical patterns. In this framework, information is physically embodied in patterns of states, configurations and transfers of matter or energy. These patterns may extend across space and time.

For example, a radio transmitter produces electromagnetic radiation whose properties vary in a controlled pattern. The radiation itself is not novel. However, the transmitter's organisation enables it to produce a particular pattern of modulation that its components cannot produce independently. The modulation is a controlled variation in a property of the transmitted radiation, such as its amplitude, frequency or phase.

A suitable receiver possesses a corresponding capability to accept the modulated signal and produce further transfers that depend upon the pattern received. The

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transmitter and receiver therefore possess different but complementary emergent capabilities.

Importantly, the physical pattern exists whether or not a recipient interprets its meaning. For example, a modulated radio signal can produce corresponding variations in electrical current within a receiving antenna, even if no message is subsequently decoded or understood. The physical effects of the pattern can therefore be distinguished from its interpretation as meaningful information.

We can therefore investigate emergence in information transfers by examining how the organisation of a transmitter enables it to produce a particular physical pattern, and how the organisation of a receiver enables it to distinguish and respond to that pattern. Information does not need to be treated as a separate physical substance because the pattern is embodied in the matter or energy being transferred, and its effects arise through physical interactions.

3.5 The Relationship Between Inputs, Processes and Outputs

The preceding examples illustrate that emergent input and output capabilities are closely related to the causal processes operating within an assembly. An incoming transfer may initiate or alter a process. The process may then produce internal transfers, change the assembly's organisation or generate outputs to its environment.

For example, the light-sensitive organism discussed in Section 3.3 receives electromagnetic radiation. Its organised processes convert the effects of that radiation into internal transfers that may influence movement or other activities.

Similarly, the radio receiver accepts a patterned electromagnetic signal and, through its internal processes, produces an electrical output that reflects the received pattern.

The distinction between input and output depends upon the boundary of the assembly being investigated. A transfer leaving one assembly may enter another, while transfers occurring within a larger assembly may be internal to that assembly. Consequently, an emergent capability may involve several connected stages of receiving, transforming and producing transfers.

The novelty of an emergent capability must therefore be investigated through the causal process and component organisation responsible for producing or accepting the transfer, rather than through the input or output alone. Different processes may establish equivalent emergent capabilities, even when they involve different components and assembly histories. The emergence of one capability does not invalidate the emergence of another simply because their outputs or inputs are equivalent.

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3.6 Causal Integration and Vanishing Properties

The formation of an assembly can establish new emergent causal capabilities. However, it may also change the ways in which its components exercise their existing capabilities. This second phenomenon is related to what may be called *vanishing properties*: properties that appear to disappear when previously independent entities become components of a larger assembly.

The properties do not necessarily vanish physically. Instead, assembly may change the causal relationships and transfers through which they are expressed.

Three mechanisms are particularly relevant:

- *Transfer internalisation* occurs when transfers that previously took place between independent entities become internal to a larger assembly. These transfers continue to occur, but they no longer cross the boundary of the parent assembly.
- *Transfer mediation* occurs when transfers between a component and the wider environment take place through other components or processes of the parent assembly, rather than directly.
- *Capability suppression* occurs when the organisation of an assembly constrains or prevents a component from exercising a capability previously available to it. The capability may remain latent if the component retains the organisation needed to exercise it. Alternatively, incorporation into the larger assembly may change the component's internal organisation sufficiently to remove the capability altogether. In the latter case, the capability has been lost rather than merely suppressed.

These changes are aspects of *causal integration*: the reorganisation of causal relationships as components become coupled within a larger assembly.

For example, a free-living cell may obtain nutrients directly from its environment and release waste products into it. When cells become organised into a multicellular organism, some may obtain nutrients through internal transport processes and deliver waste products to those processes for subsequent removal. The transfers have not disappeared. However, their pathways and relationships to the organism's boundary have changed.

As components become more strongly coupled to a parent assembly, a greater proportion of the transfers supporting their functions may become internal to, or mediated by, that assembly. Their independent capabilities may also become increasingly constrained. This is a tendency rather than a universal rule. Some components remain strongly coupled to their parent assembly while specialising in transfers across its boundary.

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The strength of causal coupling between components depends partly upon how important their interactions are to one another's functioning. For example, a component may depend upon a single essential input from another component, without which it cannot function. Conversely, it may receive numerous inputs that have little effect on its functioning. The number of transfers alone is therefore not a reliable measure of coupling strength.

Causal integration can therefore change how transfers occur within an assembly, how its components interact with their environment, and which of their existing capabilities remain available. These changes may accompany the emergence of new capabilities at the assembly level, but the two processes are distinct. Causal integration concerns changes in the relationships between components, whereas emergence concerns the establishment of capabilities that the components cannot exercise independently.

Thus, emergent properties and so-called vanishing properties can be understood as related but distinct possible consequences of causal assembly.

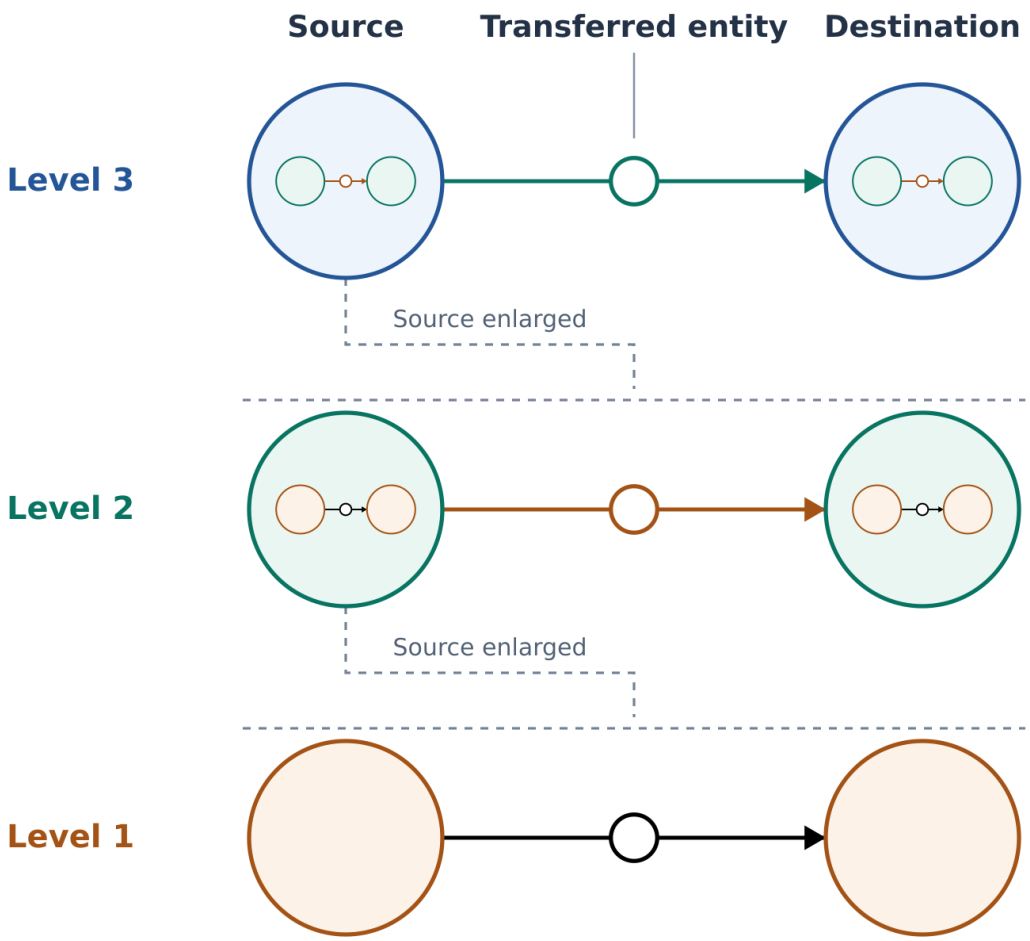


Figure 1. Causal transfers at three levels of causal organisation.

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The diagram illustrates both emergence and causal integration. It is highly simplified and idealised for the sake of clarity.

At each level, a transfer is shown as taking place between a source entity and a destination entity. Each transfer shown may be part of a wider causal network. The entity being transferred may be of a kind found at a lower level. What can emerge at the higher level is the capability to transfer it in a new way or in a new causal role.

The source and destination each comprise interacting components. At the source, these interactions enable the entity to produce an output. At the destination, they enable it to accept that transfer as an input. At Levels 2 and 3, each large circle shows one transfer between two components. An entity can contain many such interactions, which together form a causal network. In the diagram, the transfer takes the colour of the level immediately below the entities it connects, with black used for transfers at Level 1. These lower level interactions can become causally integrated in the higher level entity.

3.7 Section Summary

In summary, therefore:

- Emergence establishes new capabilities to produce or accept physical transfers. Their novelty lies in the causal organisation supporting them, rather than necessarily in the matter, energy or physically embodied information being transferred.
- Assembly can also change the ways in which components exercise their existing capabilities. Through causal integration, transfers may become internal to a parent assembly, be mediated through it, or be suppressed by its organisation. These changes help explain what has traditionally been described as *vanishing properties*.
- Emergent capabilities and causal integration are related but distinct consequences of assembly. Together, they can change which entities act as sources and recipients of transfers and how those transfers are organised.

The next section considers how emergent capabilities may persist, remain latent or disappear as their supporting organisation changes.

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4. The Duration, Latency and Loss of Emergent Capabilities

4.1 The Duration of Emergent Capabilities

Emergent capabilities depend upon the causal organisation of participating components. Consequently, their continued existence depends upon whether the organisation supporting them is sufficiently maintained.

Some emergent capabilities exist only briefly, while others remain available over extended periods. However, these are not different types of emergence. In both cases, emergence occurs when the organisation of participating components establishes and maintains a capability that those components cannot exercise independently.

The duration of an emergent capability therefore depends upon the duration of the organisation supporting it. Maintenance need not imply long-term persistence. An organisation may support an emergent capability for only a short period, but the capability exists for as long as that organisation remains sufficiently intact.

We should also distinguish between the duration of a capability and the duration of its exercise. A capability may remain available between individual causal interactions, even when it is not currently producing or accepting transfers.

4.2 Short-Lived Emergent Capabilities

Consider two molecules that interact to form a short-lived reaction complex. Their temporary organisation may enable a chemical transformation that neither molecule can bring about independently. The reaction complex therefore possesses an emergent capability while the necessary organisation exists. When the reaction is completed, the complex may disassemble into products that no longer possess that capability.

This illustrates an important distinction between an emergent capability and the effects of its realisation. A capability may exist only briefly, but the transfers or changes it produces may have consequences that continue long afterwards.

Short-lived emergent capabilities do not necessarily require a persistent system. For example, components that normally exist independently in the environment may temporarily become organised in a way that establishes an emergent capability. When the components move apart or their organisation changes sufficiently, that capability may disappear. The relevant organisation need only be maintained for as long as the capability exists.

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4.3 Longer-Lived Emergent Capabilities

Now consider an enzyme, that is, a molecule whose organisation enables it to facilitate particular chemical reactions. Its component atoms and their interactions establish a capability that those atoms do not possess independently.

When a suitable substrate encounters the enzyme, the enzyme may bind it, facilitate its transformation and release the resulting products. Afterwards, the enzyme may retain the organisation needed to facilitate further reactions. Its emergent capability therefore remains available between individual reactions.

The maintenance of an emergent capability does not mean that its supporting organisation must remain completely unchanged. Components may be replaced, configurations may change, and some internal processes may cease temporarily, provided sufficient organisational continuity remains to preserve the capability.

For example, a living organism may retain particular emergent capabilities despite the continuing replacement of many of its constituent molecules.

The continued existence of an emergent capability therefore depends upon sufficient organisational continuity, rather than the permanence of particular components.

4.4 Latent Emergent Capabilities

An emergent capability need not be continuously realised. A latent capability is an existing capability that is not currently being exercised but remains available for activation under suitable circumstances.

For example, an enzyme may retain its capability to facilitate a reaction even when no suitable substrate is present. Similarly, the generator discussed earlier retains its capability to produce electricity when it is not operating. In both cases, the relevant organisation remains in place, but the necessary inputs or conditions for realising the capability are absent.

Other circumstances may also prevent activation. A process may be inhibited by a physical constraint, or the assembly may lack a necessary input. Nevertheless, the capability remains latent so long as the organisation required to realise it is retained.

An assembly may also have the potential to acquire further emergent capabilities through changes to its organisation. For example, a collection of electronic components may be capable of forming a radio receiver, but until they are appropriately connected and organised, the collection cannot receive and decode radio transmissions. The capability does not yet exist; it can only be established through further assembly or reconfiguration.

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We should therefore distinguish between an existing emergent capability that is temporarily inactive and the possibility of establishing a new capability through subsequent organisational change.

4.5 Changes in Organisation and the Loss of Emergent Capabilities

Disassembly may remove an emergent capability by ending the organised participation of components upon which it depends. However, complete disassembly is not always necessary. A sufficiently important change in configuration or causal relationships may eliminate a capability while much of the assembly remains intact.

Because emergent capabilities depend upon causal organisation, changes in that organisation may modify or remove them. Some changes may improve an existing capability or establish an additional one. Others may inhibit a capability temporarily without removing the organisation supporting it.

For example:

- Extensive changes may destroy the organisation necessary for a capability to exist. Damage to essential electrical connections in our generator may remove its capability to produce electricity.
- If the necessary organisation remains intact but an external switch prevents operation, the capability may simply remain latent.
- If essential components or their relationships are destroyed, the capability may be lost until the necessary organisation is restored.

However, the loss of one emergent capability does not necessarily mean that all the assembly's other capabilities are lost.

4.6 Section Summary

In summary:

- Emergence occurs when causal organisation establishes and maintains a capability unavailable to the participating components acting independently.
- Emergent capabilities may exist for short or extended periods, depending upon how long their supporting organisation is sufficiently maintained.
- An emergent capability may remain latent between occasions of use.
- Changes in organisation may establish, modify or remove emergent capabilities, while changes in circumstances may activate or inhibit their exercise.
- The existence, duration and realisation of an emergent capability are distinct matters.

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The next section considers how emergent capabilities can be recognised and tested, including how to distinguish genuine causal novelty from changes in our descriptions or understanding.

5. Recognising and Testing Emergence

5.1 Purpose of the Investigation

Recognising emergence requires distinguishing genuine changes in physical reality from changes in our knowledge or understanding of it.

- *Ontological novelty* concerns something genuinely new in physical reality, such as the establishment of a causal capability that did not previously exist in an assembly.
- *Epistemic novelty* concerns something new in our knowledge or understanding. We may discover a capability that has existed for a long time or develop a new explanation of how it operates.

For example, scientists may discover that a particular molecule can facilitate a chemical reaction. This discovery is epistemically novel, but the molecule's capability may have existed long before it was recognised. Similarly, describing an existing process in a different way does not necessarily establish that a new physical capability has arisen (Bhaskar, 1975/2008).

In the present framework, ontological emergence occurs when causal organisation establishes a capability to produce or accept transfers that the participating components do not possess independently.

The purpose of investigating emergence is therefore to determine whether a particular capability satisfies this criterion and whether the available evidence supports that conclusion.

A single assembly may possess several emergent capabilities, each supported by different or overlapping causal processes. Consequently, the investigation must focus on a particular capability and the causal process that establishes it, rather than treating emergence as an undifferentiated property of the assembly.

5.2 A Practical Method for Investigating Emergence

The following seven-step method provides a systematic approach to investigating a proposed emergent capability.

Step 1 – Identify the capability.

Specify the transfer that the assembly can produce or accept and the circumstances under which this occurs.

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Step 2 – Examine the transfer.

Identify its relevant physical characteristics, including any causal organisation or information pattern embodied in the transfer.

Step 3 – Identify the causal process.

Trace the interactions responsible for producing or accepting the transfer.

Step 4 – Identify the participating components.

Determine their individual capabilities and the relationships and constraints through which they participate in the process.

Step 5 – Investigate organisational dependence.

Establish whether the capability depends upon the organisation of the participating components and whether those components could produce or accept an equivalent transfer independently.

Step 6 – Consider alternative explanations.

Determine whether the apparent novelty is instead an improvement in performance, the activation of a latent capability, or a change in description or understanding.

Step 7 – Assess the evidence.

Decide whether the available evidence supports the conclusion that a genuinely emergent causal capability exists, and identify any remaining uncertainties.

The following subsections explain the principal considerations involved in applying this method.

5.3 Steps 1 to 4: Identifying Capabilities, Transfers and Causal Processes

The investigation begins at Step 1 by identifying the capability whose emergence is being assessed. This requires specifying the transfer that an assembly can produce or accept, including any important characteristics of that transfer.

An important part of this investigation is Step 2 which concerns the physical characteristics of the transfer itself. As discussed in Section 3, a transfer may involve an assembly or collection of assemblies, or a pattern embodied in matter or energy. Where a transfer possesses an underlying causal organisation, that organisation can be investigated to determine what the relevant process produces or accepts.

For information transfers, particular attention should be given to the physical pattern carried by the transfer substrate. For example, a radio transmitter produces electromagnetic radiation with a controlled pattern of modulation. To investigate its

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emergent capability, we would examine how its components and their interactions establish the ability to produce that pattern. The pattern itself is physically real, but its novelty does not necessarily lie in the electromagnetic radiation carrying it. Rather, the novelty may lie in the organised capability to produce the particular pattern.

The same principle applies to a receiver capable of accepting the patterned transfer and responding to it.

Investigating the transfer therefore helps us specify the capability whose emergence is being assessed. However, the transfer alone cannot establish whether the capability is emergent. We must also examine the causal organisation responsible for producing or accepting it.

Steps 3 and 4 identify the relevant causal process and its participating components. The process comprises the connected physical interactions through which the transfer is produced or accepted.

For example, consider the electric generator introduced in Section 2. We can identify its capability to accept mechanical energy and produce an electrical output. We can then investigate the interactions between its rotating components, magnetic fields and electrical conductors that make this possible.

The investigation should identify the participating components, their individual capabilities, and the relationships and constraints that enable the process. The central question is whether the organisation of these components establishes a capability to produce or accept a transfer that they cannot produce or accept acting separately.

5.4 Step 5: Establishing Dependence upon Organisation

A central requirement of the proposed account is that an emergent capability depends upon the organisation of participating components. We can investigate this dependence in Step 5 by examining what happens when the relevant organisation changes.

For example, suppose the electrical connections in our generator are altered so that the intended output can no longer be produced. If the components retain their individual capabilities but the generator loses its ability to produce the output, this provides evidence that the capability depends upon their organisation.

A similar investigation can be carried out through experiments, observations or physical models. However, where direct alteration is impractical, we can use counterfactual reasoning: considering what would happen under specified alternative physical circumstances. For example, we might investigate whether the relevant components could produce an equivalent transfer without the relationships that currently support the process.

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The investigation should distinguish between changes that remove a capability and changes that merely prevent its realisation. As discussed in Section 4, a capability may remain latent when necessary inputs are absent or its operation is temporarily inhibited. Consequently, failure to observe a transfer does not, by itself, demonstrate that the capability has been lost. The aim is to establish which features of the causal organisation are necessary for the capability to exist and which circumstances are necessary for its realisation.

Evidence of organisational dependence is central to the investigation, but it must be considered alongside the capabilities of the participating components. The proposed criterion for emergence requires both that the capability depends upon their organisation and that the components cannot exercise an equivalent capability independently.

5.5 Step 6: Equivalent Capabilities and Improved Performance

Step 6 considers alternative explanations for the apparent emergence of a capability. Two distinctions are particularly important: the ability of different processes to have the same capability and the ability of change to improve the performance of an existing capability.

5.5.1 Equivalent capabilities established through different processes

An emergent capability need not be unique throughout physical reality. Different assemblies may establish equivalent capabilities through different causal processes and assembly histories.

For example, an electric generator and a solar cell can both produce electrical outputs, although they operate through different physical mechanisms. The generator uses electromagnetic induction, while the solar cell uses the photovoltaic effect. Both capabilities depend upon the organisation of their respective components. Emergence in one assembly does not invalidate emergence in the other. This is because emergence is assessed relative to the participating components and their organisation, not relative to every other process capable of producing an equivalent output.

The same principle applies to input capabilities. Different assemblies may accept equivalent transfers through different processes, and each may possess an emergent capability where its organisation establishes an ability unavailable to its components independently.

This distinction is particularly important when comparing systems from different physical domains. Equivalent capabilities do not necessarily imply equivalent causal mechanisms.

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5.5.2 New capabilities and improved performance

Changes in organisation do not always establish new emergent capabilities. Some changes improve the performance of capabilities that already exist.

For example, modifying our generator may increase its efficiency, allowing it to produce the same electrical output with less mechanical energy. This is an improvement in performance, but it does not necessarily establish a new emergent capability. Similarly, an optical system may become more sensitive to low levels of light without acquiring a fundamentally different ability to accept or distinguish incoming transfers.

However, improvements can sometimes enable an assembly to produce or accept transfers that were previously unavailable. For example, increased sensitivity might allow a light-detecting system to respond to illumination levels below its previous detection threshold. Whether this constitutes a new emergent capability depends upon how the capability is specified and whether the change establishes a genuinely new causal possibility.

We should therefore distinguish between:

- The establishment of a new capability.
- An improvement in the performance of an existing capability.
- The activation of an existing latent capability.
- A change in our knowledge or description of a capability.

These distinctions help prevent emergence from being attributed to every change in an assembly's behaviour.

5.6 Step 7: Assessing the Evidence and Uncertainty

The final stage, Step 7, is to determine how strongly the available evidence supports the conclusion that a genuinely emergent capability exists.

The investigation should establish, as far as possible, whether:

- The proposed capability and its associated transfer have been adequately identified.
- The relevant causal process and participating components are sufficiently understood.
- The capability depends upon the organisation of those components.
- The components cannot produce or accept an equivalent transfer independently.

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- Alternative explanations, such as improved performance or the activation of an existing capability, have been adequately considered.

The method does not require every investigation to involve physical experiments. Depending upon the subject, evidence may come from observation, controlled experiments, established physical theory or causal modelling.

Different forms of evidence may provide different degrees of confidence. For example, experimentally altering an assembly's organisation may provide relatively direct evidence of organisational dependence, whereas conclusions based upon counterfactual reasoning or causal modelling may depend more heavily upon assumptions about the underlying physical processes.

The investigation should therefore distinguish between conclusions supported by established evidence and those that remain provisional. In particular, where the underlying causal organisation is incompletely understood, conclusions should remain open to revision.

5.7 Section Summary

In summary:

- Recognising emergence requires investigating a particular causal capability, the transfer it produces or accepts, and the organisation of the components responsible for it. The central test is whether that organisation establishes a capability unavailable to the components acting separately.
- Different causal processes may establish equivalent emergent capabilities.
- Changes in performance, activity or understanding do not necessarily constitute emergence.
- The proposed method provides a practical basis for investigating emergence across physical domains without relying upon descriptions of complexity alone.

The next section considers how emergent capabilities establish new possibilities for causal relationships and what this means for causal levels.

6. Emergence and Causal Levels

In this paper, we use the term *causal levels* for what are broadly comparable to the more conventionally recognised *ontological levels* of reality. The term emphasises that these levels arise through the establishment of emergent causal capabilities. Unlike conventional descriptions of causal levels, however, causal levels are defined relative to particular assembly pathways and do not necessarily form a single hierarchy.

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6.1 Emergence Creates New Causal Possibilities

When an assembly acquires an emergent capability, it becomes able to produce or accept transfers that its components cannot produce or accept independently. This changes what is physically possible for the assembly and for other entities with which it may interact.

For example, an electric generator can supply electrical energy to other assemblies. Its emergent capability therefore makes possible causal relationships that would not exist without that capability. An electrical motor can accept this energy and convert it into mechanical movement. Its own emergent capability enables it to participate in a further causal relationship. When connected, the generator and motor can form part of a larger causal process.

The significance of emergence therefore extends beyond the assembly in which it occurs. It can create opportunities for new interactions, processes and assemblies. These opportunities are physically real, even when they have not yet been realised.

6.2 Causal levels

The term *ontological* refers to what exists in physical reality, rather than merely how we describe or understand it. In the present framework, every new emergent causal capability establishes a new causal level because it introduces a physically real possibility for causal interaction that the participating components do not possess independently (O'Connor, 2020).

For example, atoms may become organised into molecules, which may subsequently become components of larger molecular assemblies. Each new emergent capability establishes a further causal level relative to the preceding organisation and its capabilities.

However, not every assembly process establishes a new emergent capability. Consequently, organisational stages and causal levels do not necessarily correspond.

Causal levels are relative to *assembly pathways*: sequences of assembly processes through which physical entities become organised into larger assemblies, potentially establishing new emergent capabilities. Assembly pathways may diverge when existing assemblies participate in different subsequent assembly processes. They may also converge when entities originating from different pathways become components of a larger assembly.

Different pathways may independently establish equivalent emergent capabilities. Each constitutes an instance of ontological emergence relative to the participating components and their organisation. Causal levels therefore do not form a single

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universal hierarchy. Rather, they are relational, reflecting the pathways through which emergent capabilities arise.

For practical purposes, we can group these numerous emergent capabilities into broader categories through *epistemic compression*. Such groupings establish epistemic levels, including familiar chemical, biological and social levels. These epistemic levels can reflect genuine similarities in causal organisation and capability. Causal integration may also facilitate epistemic compression because it can make an assembly more readily recognisable as a distinct entity whose capabilities can be described without reference to all its internal interactions. However, the boundaries of epistemic levels depend partly upon the purposes of the investigator.

Thus, causal levels arise through physical emergence along assembly pathways, while epistemic levels arise through our classification and compression of those emergences.

6.3 Causal and Organisational Levels

Causal levels should be distinguished from organisational levels. An *organisational level* concerns the arrangement of entities as components of larger assemblies. For example, atoms may be components of molecules, molecules may be components of cells, and cells may be components of organisms. These relationships describe the organisation of physical entities.

However, the existence of a larger assembly does not necessarily establish a new emergent capability. As discussed in Section 2, a pre-systemic assembly may possess organisation without acquiring a maintained emergent capability. Consequently, the formation of a new organisational level does not automatically establish a new level of emergent causal capability.

Conversely, a single assembly may possess several emergent capabilities supported by different or overlapping causal processes. For example, a living cell may possess capabilities for accepting nutrients, producing particular substances, responding to its environment and maintaining aspects of its internal organisation. These capabilities need not arise simultaneously or depend upon identical processes.

It would therefore be misleading to assume that each organisational level corresponds to exactly one causal level.

The detailed relationships between nested assemblies, systems and organisational hierarchies will be considered in a subsequent paper.

6.4 Causal Integration and the Recognition of Causal Levels

Section 3.6 explained how causal integration can internalise, mediate or suppress transfers previously associated with independent components.

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These changes have implications for how we recognise source and recipient entities and, consequently, causal levels.

When components are loosely coupled, many of their transfers may continue to occur directly with their wider environment. Although the assembly may possess an emergent capability, its causal relationships may remain difficult to distinguish from those of its individual components.

As causal integration increases, more transfers may become internal to, or mediated by, the parent assembly. At the same time, emergent capabilities may enable the parent assembly to produce or accept transfers unavailable to its components independently.

The parent assembly may consequently become more readily recognisable as a distinct source or recipient of transfers.

This suggests a distinction between three characteristics:

- *Ontological emergence* concerns the establishment of a new causal capability through assembly.
- *Causal integration* concerns the extent to which the causal relationships of components are organised through the parent assembly.
- *Recognisability* concerns how readily the parent assembly can be distinguished from its components as a source or recipient of transfers.

Every genuinely new emergent capability establishes a causal level relative to its assembly pathway, regardless of how readily that level can be recognised. However, the degree of causal integration may influence its recognisability. For example, the cells of a multicellular organism may retain numerous internal capabilities while becoming increasingly dependent upon the organism's wider organisation. Many transfers that would occur directly between independent cells and their environment become internal or mediated. The organism may therefore be readily recognised as a source or recipient of transfers at its own causal level, even though its component cells continue to participate in numerous causal processes.

The distinction between levels is consequently not necessarily reflected in sharply defined or easily observable boundaries. This is particularly relevant where assembly pathways diverge or converge, or where components participate in overlapping causal processes.

It also helps explain the usefulness of epistemic compression. When an assembly's external transfers can be distinguished from its internal processes, we can often represent it as a single source or recipient without describing every transfer between its components.

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Such a representation may be useful for investigating the assembly's emergent capabilities, although it necessarily omits some of the underlying causal detail.

The distinction is therefore important: *causal levels arise through emergence, while their recognisability and the usefulness of their epistemic representation may depend partly upon causal integration*.

This provides a possible explanation for why some levels of physical organisation are readily recognisable while others are much less apparent, without implying that the latter are any less real.

6.5 Emergence and New Causal Relationships

An emergent capability may establish a new causal relationship when another entity possesses a compatible capability. For example, a flowering plant may produce nectar that an insect can consume. The plant's ability to produce nectar and the insect's ability to obtain and use it depend upon their respective causal organisations. Their interaction becomes possible because the output capability of one is compatible with the input capability of the other.

This does not mean that the capabilities must have emerged together or that either entity developed its capability for the benefit of the other. They may have arisen independently. However, once compatible capabilities exist, interactions between the entities may become possible.

Such interactions may affect the circumstances experienced by both entities and by others in their environment. Some relationships may support the persistence of the participating assemblies. Others may undermine their organisation or reduce their capabilities. Emergence therefore creates new causal possibilities, but it does not determine whether their consequences will be beneficial or harmful to particular assemblies.

6.6 Emergence Can Enable Further Emergence

New causal relationships can also create opportunities for further assembly and emergence.

Consider an assembly that acquires the capability to produce a particular substance. Other assemblies may possess or subsequently acquire capabilities that enable them to accept and use that substance. Their interactions may establish new causal processes, some of which may support further organisation.

For example, the production of oxygen by photosynthetic organisms altered the physical and chemical circumstances experienced by other organisms. Oxygen became available for chemical processes that could support additional biological capabilities. This did not mean that oxygen production automatically caused those capabilities to

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emerge. Rather, it established an important physical condition under which further evolutionary developments became possible.

The distinction is important. An emergent capability may create an opportunity for further emergence without being sufficient to bring it about. Additional components, suitable configurations, physical interactions and supporting circumstances may all be required.

Thus, emergence can contribute to a succession of new causal possibilities, but the outcome remains dependent upon the particular processes and circumstances involved.

6.7 Emergence Does Not Necessarily Increase Complexity

Although emergence can enable further emergence, it does not follow that physical reality must become progressively more complex. The following mechanisms are also possible:

- New capabilities may support the formation and persistence of additional assemblies. However, they may also undermine existing assemblies, remove capabilities or contribute to disassembly.
- The introduction of a substance into an environment may enable some chemical or biological processes while inhibiting others.
- An emergent capability may replace several existing processes with a simpler or more efficient arrangement.

Changes in causal organisation can therefore increase, decrease or redistribute complexity. The consequences depend upon the interactions between assemblies and their environments. There is therefore no general requirement that emergence must lead to increasing complexity or to the persistence of every capability that arises.

6.8 Section Summary

In summary:

- Every genuinely new emergent causal capability establishes a causal level relative to the assembly pathway through which it arises. These pathways may diverge or converge, so causal levels do not necessarily form a single universal hierarchy.
- Causal integration can influence how readily these levels are recognised. As component transfers become internalised or mediated by a parent assembly, the assembly may become more readily distinguishable as a source or recipient of transfers. However, the existence of a causal level does not depend upon its recognisability.

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- Epistemic compression allows us to group emergent capabilities into broader levels and to describe assemblies without representing every internal causal interaction.
- Emergent capabilities also establish new possibilities for causal relationships. These may support or undermine existing assemblies and create opportunities for further emergence.

The next section considers how these processes may contribute to evolutionary change.

7. Emergence and Evolution

7.1 The Relationship Between Emergence and Evolution

Emergence and evolution are closely related, but they describe different aspects of physical change:

- Emergence concerns the establishment of new causal capabilities through the organisation of physical entities.
- Evolution concerns changes over time in the characteristics, occurrence and relationships of entities and assemblies.

An emergent capability may influence whether an assembly persists, reproduces or participates in further assembly processes. Conversely, evolutionary processes may establish circumstances in which new emergent capabilities can arise. The relationship is therefore potentially reciprocal.

However, emergence does not necessarily lead to evolution, nor does every evolutionary change involve the establishment of a new emergent capability. For example, an existing capability may become more effective through changes in component organisation without establishing a fundamentally new capability.

The distinction allows us to investigate the causal relationships between emergence and evolution without treating them as the same phenomenon.

7.2 Emergent Capabilities and Persistence

An assembly's persistence depends upon the physical processes that maintain its organisation. Emergent capabilities may contribute to these processes by enabling the assembly to obtain necessary inputs, produce useful outputs or respond to circumstances that might otherwise undermine it. For example, a bacterium may possess an emergent capability to move towards a source of nutrients.

A capability can improve opportunities to obtain the materials and energy required for maintenance and reproduction. However, a capability does not guarantee persistence.

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The same capability may be advantageous in one environment and disadvantageous in another. Its effectiveness also depends upon the surrounding circumstances, including the availability of nutrients, competition and other environmental influences. Its contribution to persistence must therefore be assessed relative to the circumstances in which the assembly exists.

Nevertheless, assemblies possessing capabilities that favour their persistence under particular circumstances may survive longer than assemblies lacking those capabilities. This provides one possible connection between emergence and evolutionary selection.

7.3 Emergent Outputs and the Proliferation of Other Assemblies

The consequences of an emergent capability may extend beyond the assembly possessing it. An output produced by one assembly may become an input to another. Where the receiving assembly can use that input to support its maintenance, reproduction or further assembly, the output may contribute to its persistence or proliferation.

For example, photosynthetic organisms produce organic substances that other organisms can use as sources of matter and energy. These outputs can support the persistence and proliferation of organisms that possess suitable capabilities to accept and use them.

This relationship does not necessarily require the producing organism to benefit from the receiving organism. Nor does it require either organism to possess a purpose directed towards supporting the other. The relationship can arise from the compatibility of their causal capabilities and the circumstances in which they interact.

Over time, such relationships may alter the relative occurrence of different assemblies within an environment. In this way, an emergent capability may influence evolutionary developments beyond the assembly in which it arose.

7.4 Circular Networks of Supporting Interactions

Supportive relationships need not be limited to direct exchanges between two assemblies. They may also occur through networks of interacting assemblies.

Consider three types of organisms, A, B and C.

- Organisms of type A produce an output that supports the persistence of B.
- Organisms of type B produce an output that supports C.
- Organisms of type C produce an output that supports A.

The resulting circular network may contribute to the persistence or proliferation of all three types, even though no pair necessarily exchanges benefits directly.

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Such networks can also involve more complicated arrangements, including branching and converging causal pathways. The important feature is that outputs from some assemblies contribute, directly or indirectly, to circumstances that support the continued existence of others.

However, the existence of a circular network does not guarantee its persistence. Changes in the availability of inputs, the loss of participating assemblies or the introduction of competing processes may undermine the network.

The network may also contain interactions that are beneficial to some participants but harmful to others. Consequently, its persistence depends upon the combined effects of the causal relationships involved.

These relationships may arise without deliberate coordination or any shared purpose.

7.5 Successive Emergence During Evolution

Evolutionary developments may involve successive emergences of different causal capabilities. The evolution of vision provides a useful illustration:

- A simple light-sensitive organism may possess the capability to detect the presence or intensity of illumination.
- Further changes in organisation may establish the capability to distinguish the direction from which light arrives.
- Other developments may establish capabilities to detect spatial patterns, distinguish shapes or respond to movement.

Each genuinely new capability represents a separate instance of emergence because it establishes a causal possibility unavailable through the preceding organisation (Szathmáry & Maynard Smith, 1995).

However, not every evolutionary improvement constitutes a new emergence. For example, an increase in the sensitivity of an existing light-detection mechanism may improve its performance without establishing a different kind of capability. Similarly, improvements in image resolution may enhance an existing capability to distinguish spatial patterns. The distinction depends upon the capabilities being investigated and the causal processes supporting them.

This example should not be interpreted as a single historical sequence through which all eyes necessarily evolved. Different evolutionary pathways have produced different visual systems, and similar capabilities may have arisen through different organisations. The important point is that evolutionary change can involve both improvements in existing capabilities and the establishment of genuinely new ones.

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7.6 Emergence and Environmental Change

The emergence of a new capability may alter the circumstances experienced by other assemblies. For example, the emergence and proliferation of oxygen-producing photosynthetic organisms contributed to major changes in Earth's atmospheric and chemical conditions (Lyons et al., 2014).

Similarly, the evolution of mobility and new feeding capabilities in early marine animals altered the circumstances experienced by other organisms. During the Ediacaran–Cambrian transition, mobile animals increasingly grazed upon microbial mats and disturbed the sediments of the seabed. These activities could deplete food resources, destabilise habitats and interfere with the feeding processes of organisms dependent upon relatively undisturbed conditions. Such changes are thought to have contributed to the decline of some earlier marine communities, although other environmental factors may also have played a part (Bottjer et al., 2000).

These changes created opportunities for some biological processes while undermining organisms and processes poorly suited to the altered conditions. They also changed the circumstances in which further assembly and emergence could occur.

This illustrates how the consequences of emergence can be both supportive and destructive, influencing the subsequent evolution of other assemblies without necessarily determining its direction.

7.7 A Possible General Evolutionary Mechanism

The preceding discussion suggests a possible general relationship between emergence and evolution:

- An assembly acquires a new emergent capability through a change in causal organisation.
- That capability enables it to produce or accept transfers that were previously unavailable to it.
- These transfers may alter the circumstances experienced by the assembly itself or by other assemblies.
- Where the resulting changes support the maintenance, reproduction or further assembly of particular entities, those entities may become more prevalent.
- Their increased occurrence may, in turn, alter the environment and create opportunities for further assembly and emergence.

The process may therefore involve recurring interactions between:

- The emergence of new causal capabilities.
- Changes in transfers and causal relationships.
- Changes in the persistence or proliferation of assemblies.

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- Changes in the circumstances available for further assembly and emergence.

These interactions may form reinforcing or undermining causal pathways.

The proposed mechanism does not imply that emergence always produces evolutionary change or that evolutionary developments necessarily increase complexity. Nor does it replace established explanations of biological evolution, in which reproduction, heritable variation, including random mutation, and natural selection play significant roles. Rather, biological evolution can be understood as a particular case within a broader account of evolutionary change involving causal assembly, emergence and changes in the persistence and proliferation of assemblies. Whether this broader account can adequately explain evolutionary processes across different physical domains remains a hypothesis requiring further investigation.

7.8 Section Summary

In summary:

Emergence and evolution are distinct but potentially interconnected processes.

- Emergent capabilities may influence the persistence and proliferation of assemblies by changing the transfers they can produce or accept.
- Their consequences may extend through networks of interacting assemblies, including circular networks of mutually supportive relationships.
- Evolutionary developments may involve successive emergences of new capabilities alongside improvements in capabilities that already exist.
- The resulting changes may create opportunities for further emergence, but they may also undermine existing assemblies or reduce complexity.

This suggests a possible general relationship between emergence, causal interactions and evolutionary change that warrants further investigation.

8. Discussion

8.1 The Contribution of the Proposed Account

The preceding sections propose that emergence can be understood through the causal organisation of physical entities and the capabilities that organisation establishes. The central proposition is that an emergent causal capability enables an assembly to produce or accept transfers that its participating components cannot produce or accept independently.

This approach provides a basis for explaining emergence through physical mechanisms rather than treating it simply as the appearance of unexpected properties or behaviours.

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It also provides a common framework for investigating emergence across different physical domains. Chemical reactions, biological functions, technological processes and social interactions involve different components and mechanisms. Nevertheless, the proposed account suggests that their emergent capabilities can be investigated using the same general causal principles.

This does not mean that the processes are identical or that their differences are unimportant. Rather, it proposes that emergence has a common causal character despite the diversity of the physical mechanisms involved.

An important contribution is the distinction between an emergent capability and its realisation. A capability may exist without being exercised, and its continued existence depends upon the organisation supporting it. This enables the framework to accommodate transient, persistent and latent emergence without treating every occurrence of an output as a separate emergence.

8.2 Emergence Without New Fundamental Physical Laws

The proposed account is consistent with the view that physical reality operates through established physical interactions. When components become organised into an assembly, their relationships may enable causal processes that they cannot undertake independently. The resulting capability is physically real, but it does not necessarily require the introduction of a new fundamental force, substance or physical law.

For example, an enzyme's catalytic capability depends upon its molecular organisation and the physical interactions involved in binding and transforming substrates. Similarly, the electrical output of a generator depends upon electromagnetic interactions operating within a particular organisation of components.

In both cases, the emergent capability can be explained through the participating components, their interactions and the organisation supporting the relevant causal process.

This does not make the emergent capability merely a description. The organisation establishes a real difference in what the assembly can do. The proposed account therefore accommodates the ontological reality of emergence while remaining consistent with a physicalist understanding of causality (Bhaskar, 1975/2008).

8.3 The Relationship to Other Accounts of Emergence

Emergence has been discussed in several different ways within philosophy and science. Some accounts emphasise the appearance of properties or behaviours that cannot readily be predicted from knowledge of the components. Others distinguish between *weak emergence*, in which higher-level behaviour can in principle be explained through lower-level interactions, and *strong emergence*, which is sometimes taken to involve

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causal powers or laws that cannot be reduced to those interactions (Bedau, 1997; O'Connor, 2020).

The present account approaches the question differently. Rather than defining emergence primarily in terms of predictability or reducibility, it asks whether causal organisation establishes a capability unavailable to the participating components acting independently. This shifts attention from the limitations of our knowledge to the physical mechanisms responsible for the capability.

A capability may be emergent even when its operation is entirely predictable from an accurate causal model. Conversely, behaviour that is difficult to predict is not necessarily emergent. The difficulty may arise from incomplete information, computational limitations or an inadequate model. The distinction between ontological and epistemic novelty is therefore fundamental.

The proposed account does not require the stronger claim that emergent capabilities operate independently of their physical foundations. Instead, it treats them as real capabilities established through the organisation of physical processes. This position is compatible with the Critical Realist recognition of causal powers and mechanisms, while grounding the proposed explanation in physical interactions.

However, the relationship between this account and alternative philosophical treatments of emergence warrants more detailed examination.

8.4 Emergence, Causal levels and Epistemic Compression

The proposed account has implications for how we understand levels of physical reality. Every genuinely new emergent causal capability establishes a causal level relative to the assembly pathway through which it arises. These pathways may diverge or converge, so causal levels do not necessarily form a single universal hierarchy.

However, the existence of a causal level and our ability to recognise it are different matters. As components become more causally integrated, transfers that previously occurred between independent entities may become internal to, or mediated by, their parent assembly. Other transfers may be suppressed. These changes help explain the phenomenon traditionally described as *vanishing properties*.

Such changes can make the parent assembly more readily distinguishable as a source or recipient of transfers, particularly where it also possesses emergent capabilities. The degree of causal integration may therefore influence how clearly we can recognise a causal level, although it does not determine whether that level exists.

This provides a possible causal explanation for why some levels of physical organisation appear relatively distinct while others are difficult to separate from their components.

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It also helps explain the usefulness of epistemic compression. When investigating an assembly as a whole, we can often represent it through its inputs, outputs and emergent capabilities without describing every internal causal interaction.

Broader classifications, such as chemical, biological and social levels, are further epistemic compressions that group numerous emergent capabilities and processes according to their similarities and the purposes of the investigator.

Thus, causal levels arise through physical emergence, while epistemic levels are constructed to help us understand and explain that reality. Causal integration can influence the recognisability of causal levels and, consequently, the usefulness of particular epistemic compressions.

This distinction provides a possible connection between the physical organisation of systems and the hierarchical descriptions commonly used in General Systems Theory.

8.5 Emergence and Evolutionary Change

The relationship between emergence and evolution is another potentially important consequence of the proposed account. Emergent capabilities can establish new causal relationships between assemblies. These relationships may influence their maintenance, reproduction, proliferation or disassembly. The resulting changes may alter the circumstances in which further assembly and emergence can occur.

This suggests a possible recurring relationship between the emergence of capabilities, changes in causal relationships and changes in the persistence and occurrence of assemblies. The relationship may operate through direct interactions or more extensive causal networks, including circular networks of mutually supportive relationships.

However, the proposed generalisation should be treated cautiously. Biological evolution involves established mechanisms of reproduction, heritable variation, including random mutation, and natural selection. Other forms of evolutionary change may operate through different mechanisms.

The proposed account does not replace these explanations. Instead, it seeks to identify more general causal relationships that may operate across different domains. Whether those relationships are sufficiently general to support a broader theory of evolution remains a question for further investigation.

8.6 Hypotheses and Limitations

The proposed account draws upon established physical principles but also contains broader theoretical propositions that require testing.

The principal hypothesis is that emergent causal capabilities across different physical domains can be explained through the organisation of participating components and

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the causal processes that enable them to produce or accept transfers unavailable to those components independently.

Several related propositions also require investigation:

- The proposed criterion for emergence must be tested against a wide range of examples, including cases in which the distinction between a new capability and improved performance is uncertain.
- The treatment of causal levels as relative to assembly pathways requires further development. In particular, the relationships between converging pathways, equivalent capabilities and successive emergences need to be examined.
- The proposed relationship between emergence and evolutionary change requires testing across physical domains. It should not be assumed that mechanisms identified in biological evolution apply unchanged elsewhere.
- The practical identification of emergent capabilities depends upon the adequacy of the available causal explanation.

In complex assemblies, the participating components and their interactions may not be fully understood. Apparent emergence may therefore reflect limitations in our knowledge rather than the establishment of a genuinely new capability.

The reverse difficulty is also possible. An emergent capability may be overlooked because its contribution is distributed across numerous interactions or because it is not currently being exercised.

These limitations reinforce the need for careful causal investigation and for distinguishing established findings from provisional explanations.

8.7 Implications for General Systems Theory

The proposed account offers a possible foundation for a more causally grounded General Systems Theory. Rather than identifying systems primarily through observed patterns of behaviour, it defines them through organised assemblies possessing maintained emergent causal capabilities.

This provides a basis for distinguishing systems from pre-systemic assemblies and for investigating how systems arise, persist, change and disassemble. It also connects emergence with causal assembly, physical transfers, organisational constraints and latent causal potential.

These relationships may help explain why similar capabilities can arise through different processes and why different systems can participate in compatible causal relationships.

The framework also offers a basis for investigating how emergent capabilities become incorporated into larger assemblies and causal networks.

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However, the present account is not intended to provide a complete theory of hierarchical organisation, information, evolution or system viability. Those subjects require further development within the wider GST programme. The contribution of this paper is to propose a general causal explanation of emergence that can support those developments while remaining open to empirical and theoretical testing.

9. Conclusions

This paper has proposed a general causal account of emergence, building upon the physical foundations established in *Causal Assembly Theory: Assembly and Disassembly as Causal Processes*. Its central proposition is that emergence occurs when the organisation of participating components establishes a capability to produce or accept physical transfers that those components cannot produce or accept independently.

The proposed account treats emergence as a physically real consequence of causal organisation, rather than merely an unexpected observation or a limitation of our understanding. It provides a common basis for investigating emergence across different physical domains while recognising that the underlying components and causal processes may differ considerably.

The paper has also developed several related propositions. These concern the persistence and latency of emergent capabilities, the distinction between emergence and causal integration, the establishment and recognition of causal levels, and the possible contribution of emergence to evolutionary change. Together, they suggest that phenomena often treated separately may be understood through a common framework of physical assembly, causal organisation and transfers.

An important practical contribution is the proposed method for recognising and investigating emergence. By identifying the relevant capability, transfer, causal process and participating components, and examining their organisational dependence, the method provides a basis for distinguishing genuine emergence from improvements in performance, the activation of existing capabilities or changes in our understanding.

The wider applicability of this account remains to be established. In particular, its proposed interpretation of causal levels and its relationship to evolutionary change require further theoretical development and testing across different physical domains.

The principal contribution of the paper is therefore a candidate general causal explanation of emergence that can be tested, challenged and refined. It also provides a foundation for subsequent investigations of hierarchical organisation, causal networks and other aspects of General Systems Theory.

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Definitions

A. Existing Definitions

D1.4 – Ontology

The branch of philosophy concerned with the nature of existence and the kinds of things that exist. Ontology addresses what exists in reality, independent of whether those entities are known or observed.

D2.21 – Causal Relationship

A physically instantiated process involving the transfer of matter, energy, or information between entities.

D5.7 – Transfer

The physical passage or transmission of matter, energy, or information through a causal relationship.

D5.8 – Assembly

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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

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

D5.10 – System

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.

D5.13 – Organisation (Technical)

The network of causal interactions between the constituent components or processes of an assembly or system.

D5.17 – Component

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.

D5.21 – 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.

D6.29 – Causal Mechanism

The causal organisation of processes, transfers, conditions and constraints through which a particular effect or behaviour is produced, sustained, modified or inhibited.

D7.7 – Causal Coupling

Causal coupling exists where the state or behaviour of one component causally constrains, enables or influences the possible states or behaviour of another.

D7.8 – Organisational Continuity

Organisational continuity is the continuity between successive organisational states of an entity despite possible changes in its components, configuration, relationships,

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constraints or component roles. Continuity can accommodate organisational change without requiring an unchanged overall pattern.

D7.10 – System-Level Causal Capability

A system-level causal capability is a capability to produce or accept transfers that depends upon an assembly's maintained organisation and is not possessed by its components acting separately.

D7.11 – Causal Emergence (Updated)

See D5.21 – Emergence. The terms *causal emergence* and *emergence* are synonymous within this framework.

D7.16 – Latent Causal Potential

Latent causal potential comprises physically embodied causal capabilities that are not currently realised because the relevant interacting entities, inputs or enabling conditions are absent, or because constraints inhibit their operation.

B. New Definitions

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.

D8.4 – Capability Suppression

Capability suppression occurs when the organisation of an assembly constrains or prevents a component from exercising a capability that would otherwise be available to it. The capability may remain latent if its supporting organisation is retained, or may be lost if that organisation is sufficiently altered.

D8.5 – Causal Level

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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.

Propositions

A. Existing Propositions

P2.5 – Transfer Proposition

A causal relationship involves the transfer of matter, energy, or information between entities.

P5.7 – Emergent Causation

Emergence gives rise to new causal capabilities that are not available to the interacting components considered in isolation.

P6.1 – Physical Instantiation of Causality

Causal influence between separate processes is physically instantiated through transfers of matter, energy or physically embodied information. No causal influence can pass between separate processes without a physical transfer connecting them.

P6.19 – Emergence Proposition

Emergent properties arise from the organisation and causal interaction of components and are not exhibited by those components considered independently.

P7.8 – Persistent Organisation Provides Causal Potential

Once established, an assembly's organisation, together with its components' properties, can enable or constrain subsequent causal processes. Appropriate interacting entities, input transfers and conditions can realise this potential. The

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processes currently realised need not exhaust the assembly's physically embodied capabilities, and changed circumstances may permit previously latent capabilities to operate.

P7.9 – Assembly Can Alter System-Level Causal Capability

Assembly may establish configurations, relationships and constraints that enable, inhibit or coordinate the existing properties and capabilities of components in ways unavailable while those entities were independently organised.

P7.15 – Disassembly Can Alter Causal Capability Independently of Component Survival

Partial disassembly may remove or modify system-level causal capabilities while leaving others intact, while complete disassembly removes capabilities dependent upon the organisation of the former assembly even though its former components may persist.

P7.20 – Causal Processes Can Modify the Organisation Through Which Subsequent Causality Occurs

Assembly, disassembly and reassembly may construct, modify or remove components, relationships and constraints and thereby alter the causal network through which later processes operate.

P7.21 – Assembly Can Operate Recursively

An assembly may itself become organised as a component of a more extensive assembly while retaining its own internal organisation. An entity may consequently be an assembly relative to its components and simultaneously a component relative to a more extensive entity.

P7.22 – Existing Assemblies Can Alter the Causal Conditions for Further Assembly

Through their system-level causal activities, existing assemblies may produce, concentrate, direct or transport matter, energy or information required for assembly elsewhere and can therefore alter circumstances, conditions or constraints affecting subsequent assembly.

P7.26 – Organisational Effects Are Relative to a Specified Entity, Level and Timescale

Whether a process supports or undermines organisation must be assessed relative to a specified entity, organisational level and timescale. Disassembly or disruption at one level may contribute to persistence at another, while support for one component may undermine the assembly containing it.

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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 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.

P7.31 – Increasing Complexity Proposition (Hypothesis)

Existing organisation may contribute to increasing organisational complexity by creating causal conditions that enable further assembly, although assembly does not imply that complexity must continually or monotonically increase.

P7.33 – Causal Emergence Proposition (Hypothesis)

An assembly may possess an emergent causal capability where its maintained organisation enables it to produce or accept transfers that its components cannot produce or accept acting separately. This capability can persist while inactive, provided the organisation sustaining it is maintained.

P7.34 – Organisational Dependence Proposition (Hypothesis)

Where a capability appears following assembly and is lost or modified when the relevant organisation is disrupted, while component capabilities remain substantially unchanged, this provides evidence that the organisation contributes to that capability.

B. New Propositions

P8.1 – Emergence and Duration Proposition

An emergent causal capability exists for as long as the organisation required to support it is sufficiently maintained. Its duration may be brief or extended, and the duration of its existence need not correspond to the duration of the transfers produced through its exercise.

P8.2 – Emergence–Integration Distinction Proposition

Causal integration and emergence are distinct phenomena. Integration may modify the expression of existing component capabilities without establishing a new emergent capability. Conversely, an emergent capability may arise without extensive integration of the participating components' other causal relationships.

P8.3 – Component Capability Expression Proposition

The incorporation of an entity into a more extensive assembly may alter how its existing capabilities are expressed through transfer internalisation, transfer mediation or capability suppression. An apparent loss of capability at the component level does not necessarily imply the destruction of the underlying capability.

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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.

P8.5 – Causal Integration and Epistemic Compression Proposition (Hypothesis)

Causal integration may make an assembly more readily recognisable as a distinct source or recipient of transfers, thereby facilitating epistemic compression of its internal causal organisation. The ease with which an assembly is recognised as a distinct entity does not necessarily indicate whether emergence has occurred.

P8.6 – Emergence and Further Emergence Proposition (Hypothesis)

An emergent capability may alter the causal circumstances experienced by other assemblies, creating opportunities for further assembly and emergence that would otherwise be unavailable. These effects may operate through direct transfers or through changes to wider causal networks and environmental conditions.

P8.7 – Emergence and Evolutionary Change Proposition (Hypothesis)

Emergent causal capabilities may influence evolutionary change by altering the conditions affecting the persistence, proliferation, modification or disassembly of assemblies. Where these effects recur, they may contribute to successive changes in the organisation and capabilities of physical systems.

P8.8 – Non-Directional Evolution Proposition (Hypothesis)

Emergence does not necessarily lead to increasing organisational complexity. Its consequences may include the establishment of more complex organisations, the simplification or replacement of existing organisations, or their partial or complete disassembly. The direction of evolutionary change depends upon the causal circumstances and constraints involved.

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