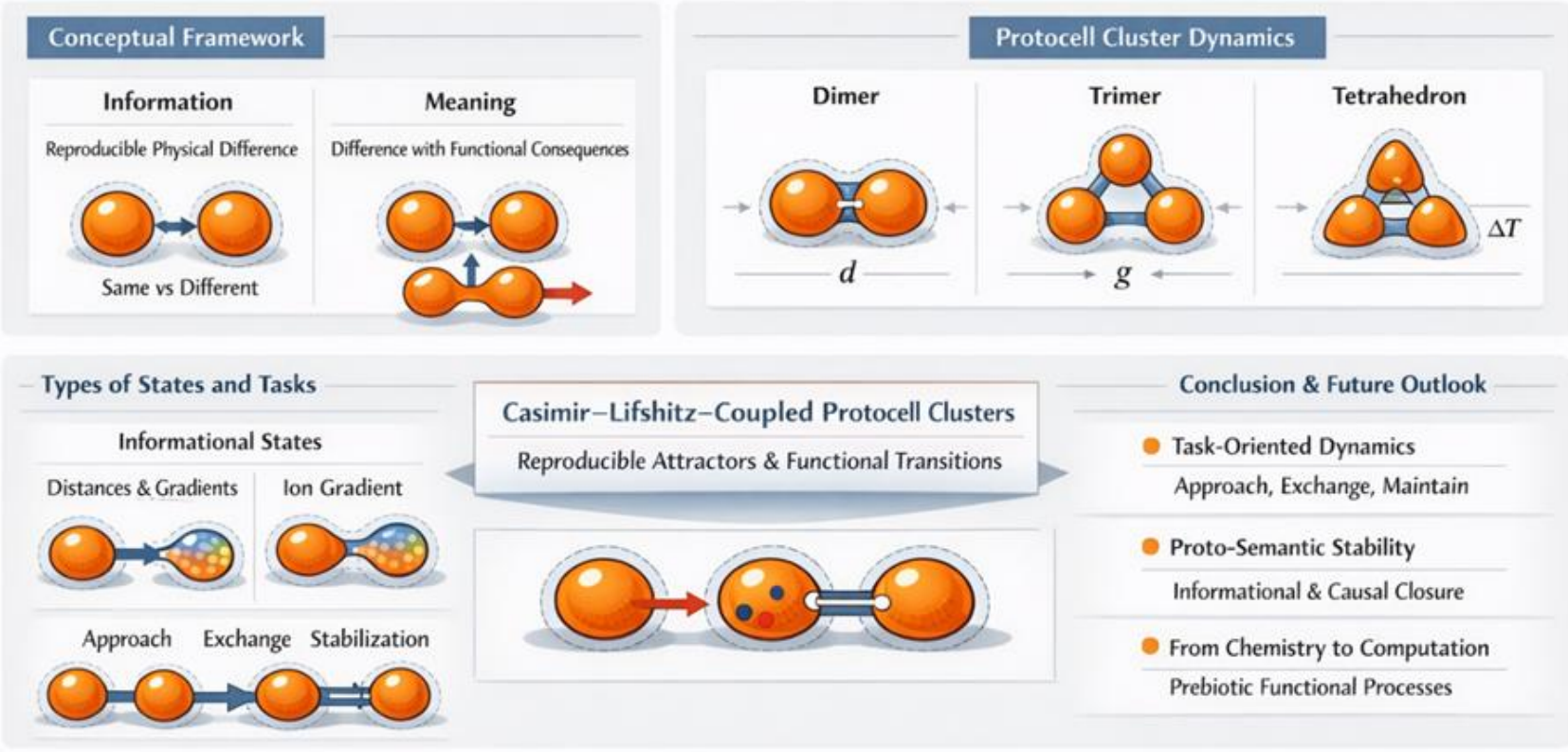
# From Physical Difference to Meaning: A Constructor-Theoretic Framework for Prebiotic Information in Casimir-Lifshitz-Coupled Protocell Clusters

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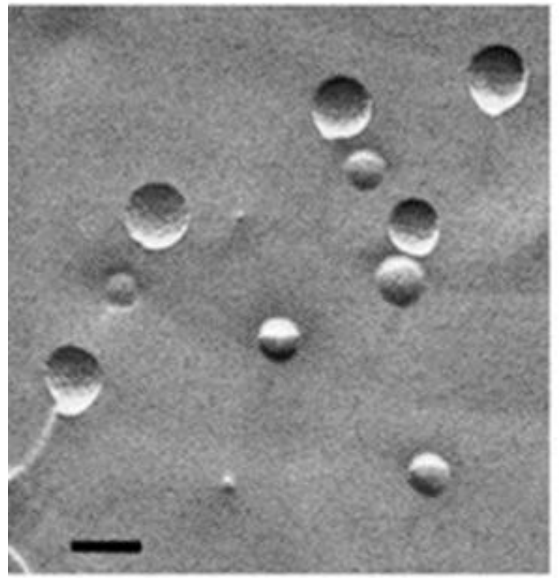
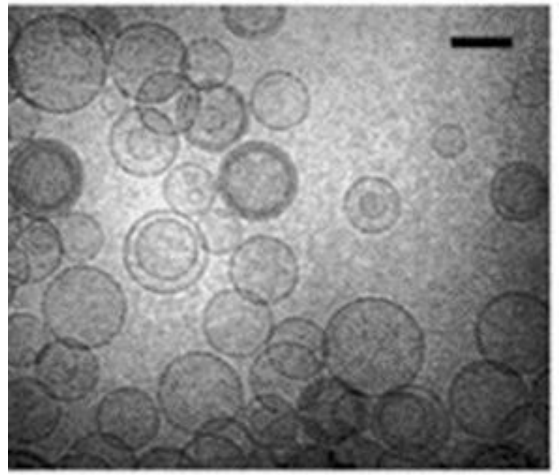
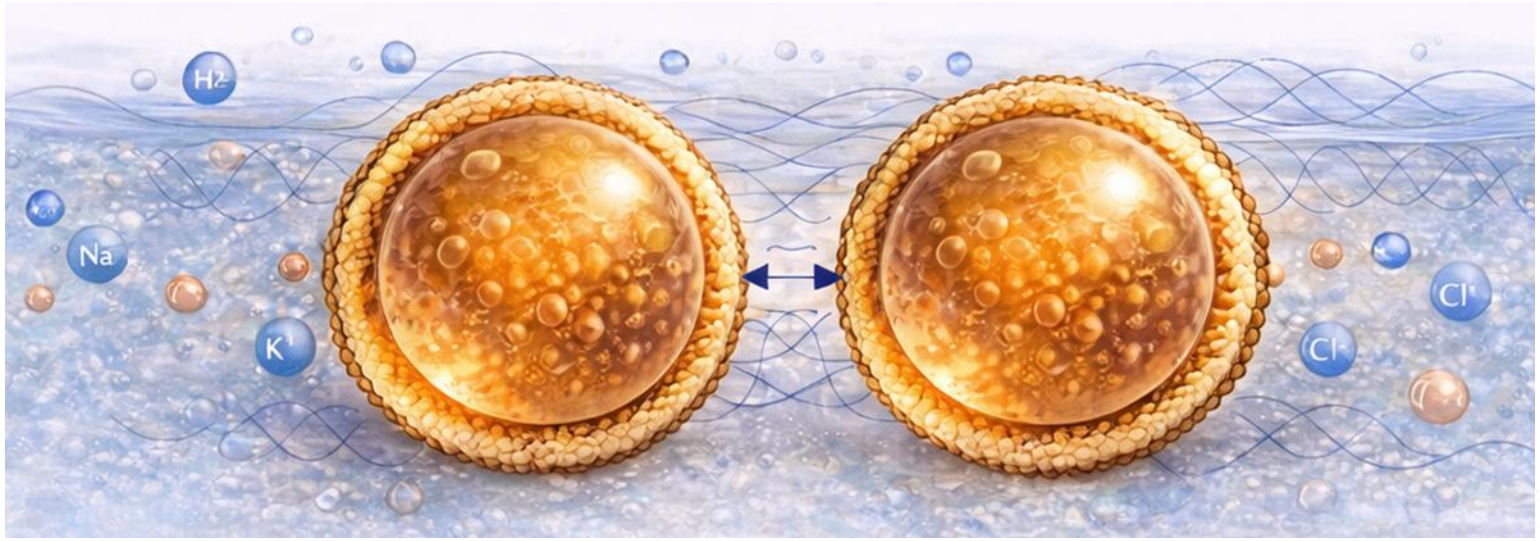
BIOTECHNO-2026 | Valencia

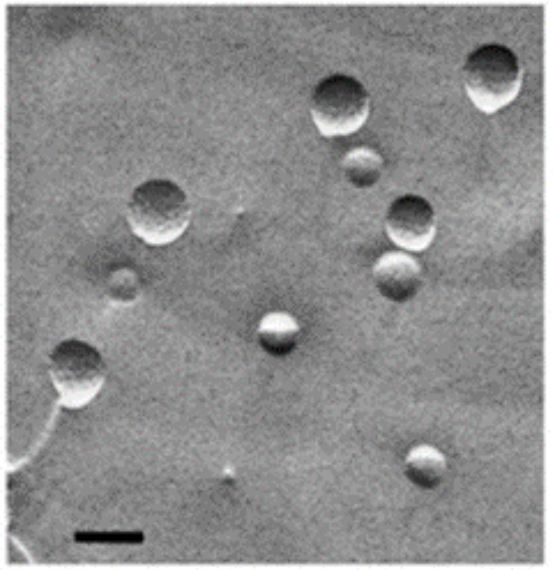
# First Protocells appeared 4.2 billion years ago

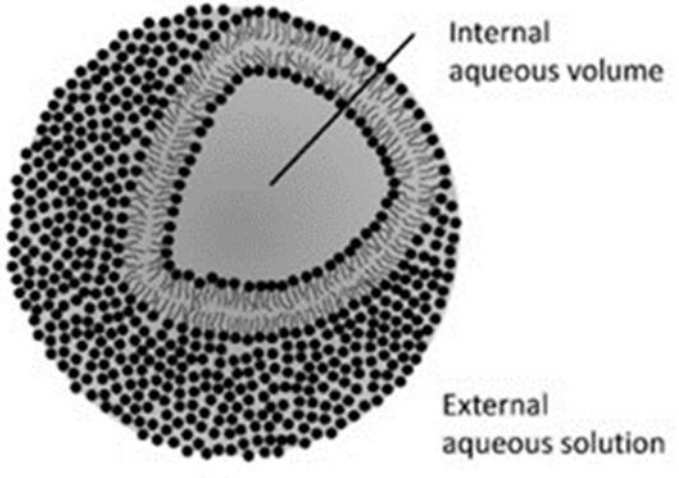


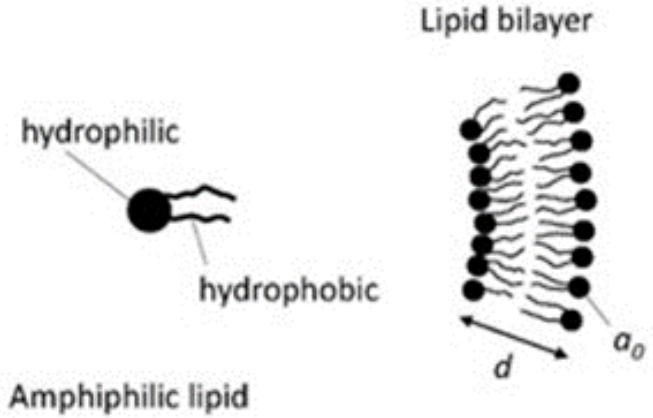


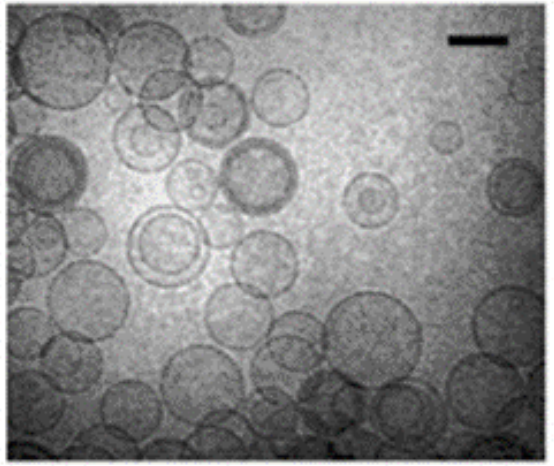
# The prebiotic Protocells:





# Scientific Motivation

One of the central questions in origin-of-life research is:

**How could information emerge before genes, enzymes, or symbolic genetic codes existed?**

Most biological theories assume information already exists in molecular polymers such as RNA or DNA.

**Constructor Theory** proposes a different perspective:
**information is not abstract but a physical property defined by the laws of physics.**

# Research Questions

- **RQ1:** Under which physical conditions can protocell clusters act as constructors (repeatable tasks)?
- **RQ2:** How to distinguish informational differences from meaningful states with distinct outcomes?
- **RQ3:** Which task classes support proto-semantic stability and relate to closure/ε-machines?

# Conceptual Gap

Classical information theory (**Shannon**) assumes:

- senders and receivers
- symbolic messages
- communication channels

These assumptions **do not exist** in prebiotic environments.

**Constructor Theory** instead asks:

**Which physical transformations are possible**
**and which are impossible according to the laws of physics?**

# Why Constructor Theory (CT)?

- Origin-of-life models often describe **patterns** but **not when patterns** become **functional**.
- CT describes laws via tasks: what **transformations** are **possible** or **impossible**.
- **Meaning** becomes a **physical question**: **which differences control** downstream tasks?

## Constructor theory of information

**08.02.2015**

David Deutsch[1] and Chiara Marletto[2]

[1]Centre for Quantum Computation, The Clarendon Laboratory, University of Oxford, Oxford OX1 3PU, and [2]Materials Department, University of Oxford, Oxford OX1 3PH, UK

We propose a theory of information expressed solely in terms of which transformations of physical systems are possible and which are impossible—i.e. in constructor-theoretic terms. It includes conjectured, exact laws of physics expressing the regularities that allow information to be physically instantiated. Although these laws are directly about information, independently of the details of particular physical instantiations, information is not regarded as an *a priori* mathematical or logical concept, but as something whose nature and properties are determined by the laws of physics alone. This theory solves a problem at the foundations of existing information theory,

# CT Basic Ideas: Tasks and Constructors

**Constructor Theory** reformulates physics **in terms of tasks**.

A **task** describes a **transformation**: **{input attribute → output attribute}**

A **constructor** is a system capable of performing a task
repeatedly while remaining able to perform it again.

**Examples** include enzymes, machines, or stable protocell clusters.

- **Task: A = {$x_i$ → $y_i$}** maps input attributes to output attributes.
- **Constructor:** performs the task repeatedly while retaining its ability to do so.
- **Key:** not perfect accuracy now — but possible to arbitrarily improve in principle.

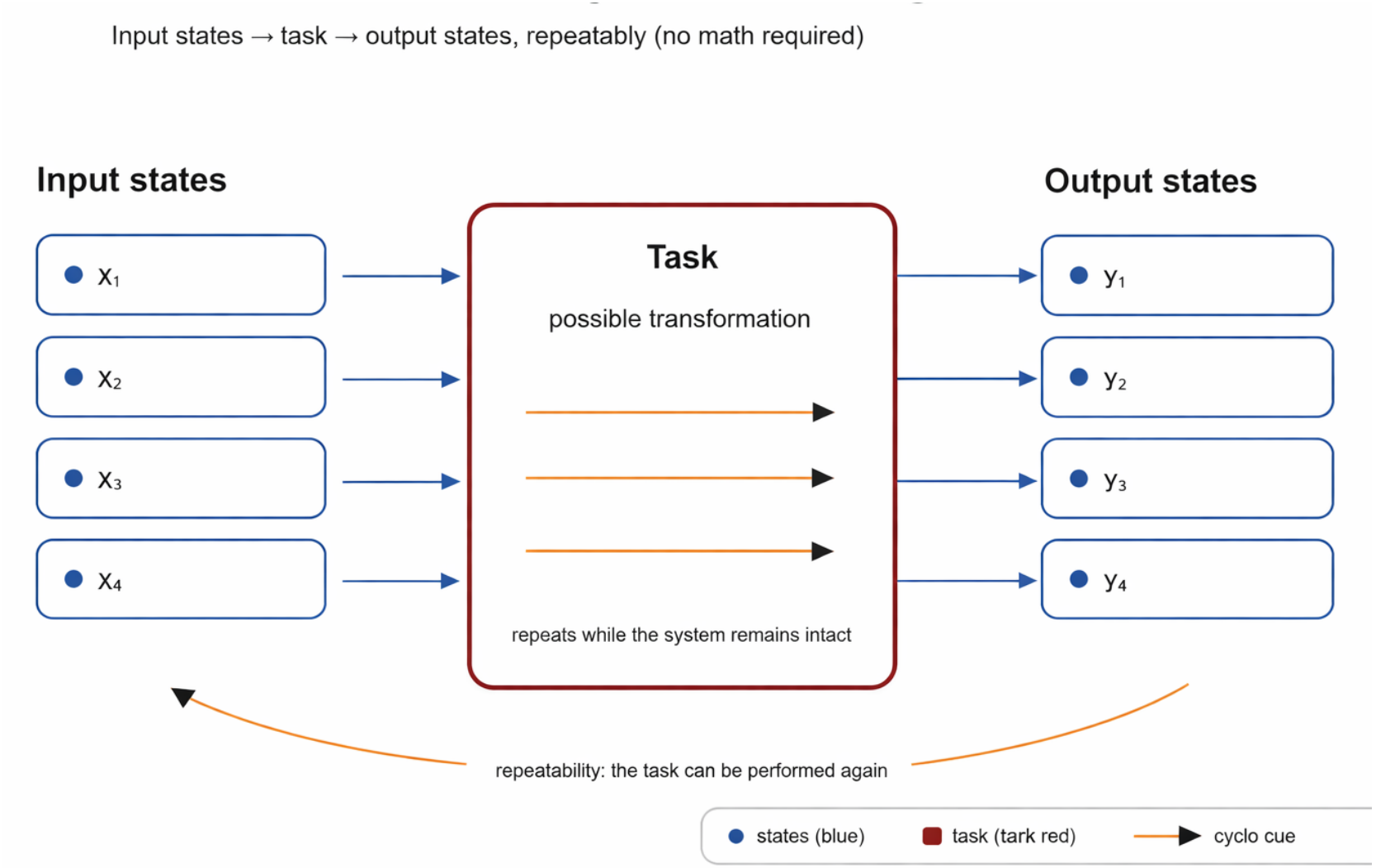
# Possible vs impossible Tasks

In Constructor Theory, **physical laws** are expressed as **constraints on tasks**.

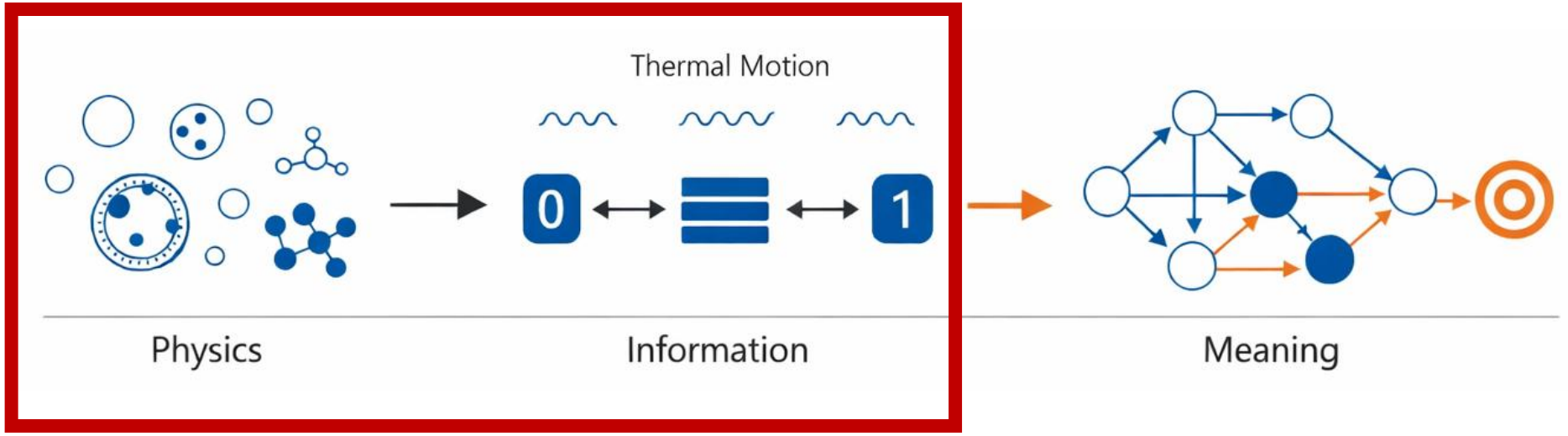
A **task** is **possible** if the laws of physics allow a constructor to perform it with arbitrarily high accuracy.

A **task** is **impossible** if it violates fundamental principles such as energy conservation or the quantum no-cloning theorem.

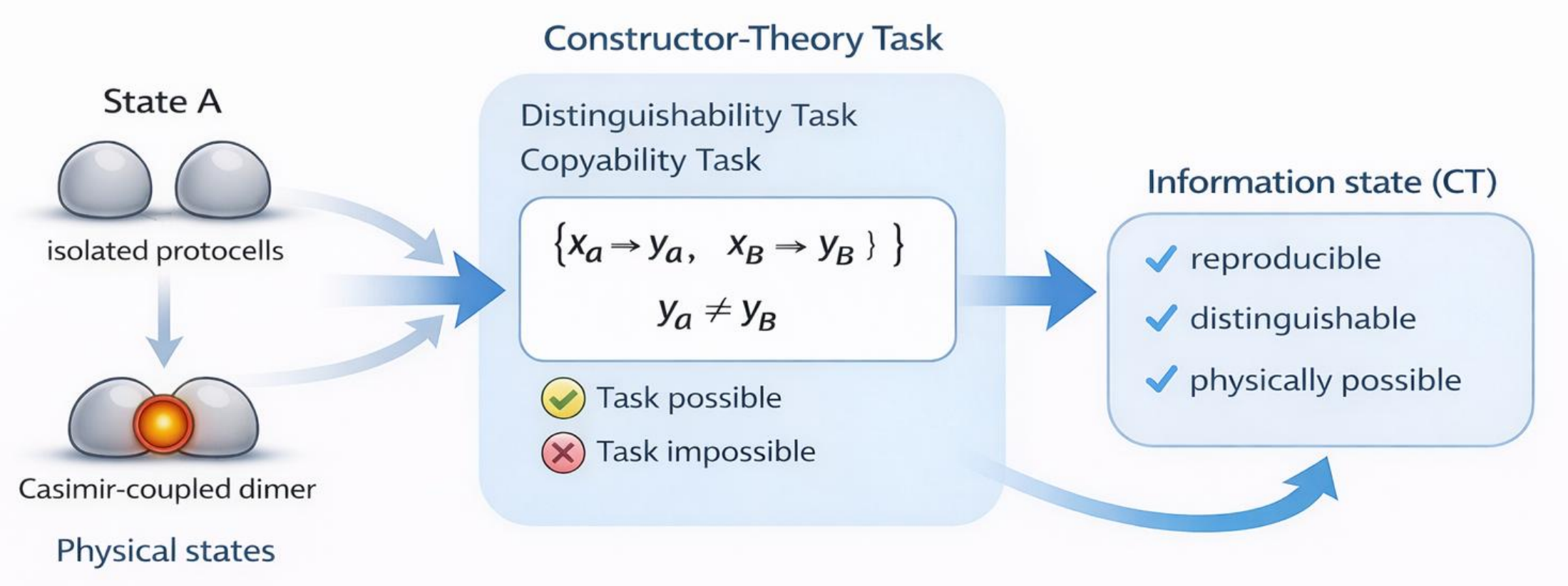
# Constructor Theory in one image



# Our Journey: From physical difference to meaning



# From physical difference to information in Constructor Theory



# Information in CT: a reproducible physical difference

**Information** in CT is defined as a **reproducible physical difference**.

Two states carry information if tasks exist that can:

- distinguish them
- copy them
- transform them reliably

Information therefore depends on the space of physically possible transformations.

- A **difference** counts as **information** only if tasks exist to generate / distinguish / copy it.
- **No symbols required:** a ‘bit’ is defined by physically possible task families.
- In protocell clusters: distances, geometries, contact graphs, gradients can be such differences.

# Information variables in CT

A system carries information when its states form an information variable.

An information variable is a set of attributes that can:

- be permuted (computation)
- be copied (cloning task)
- be distinguished by measurement

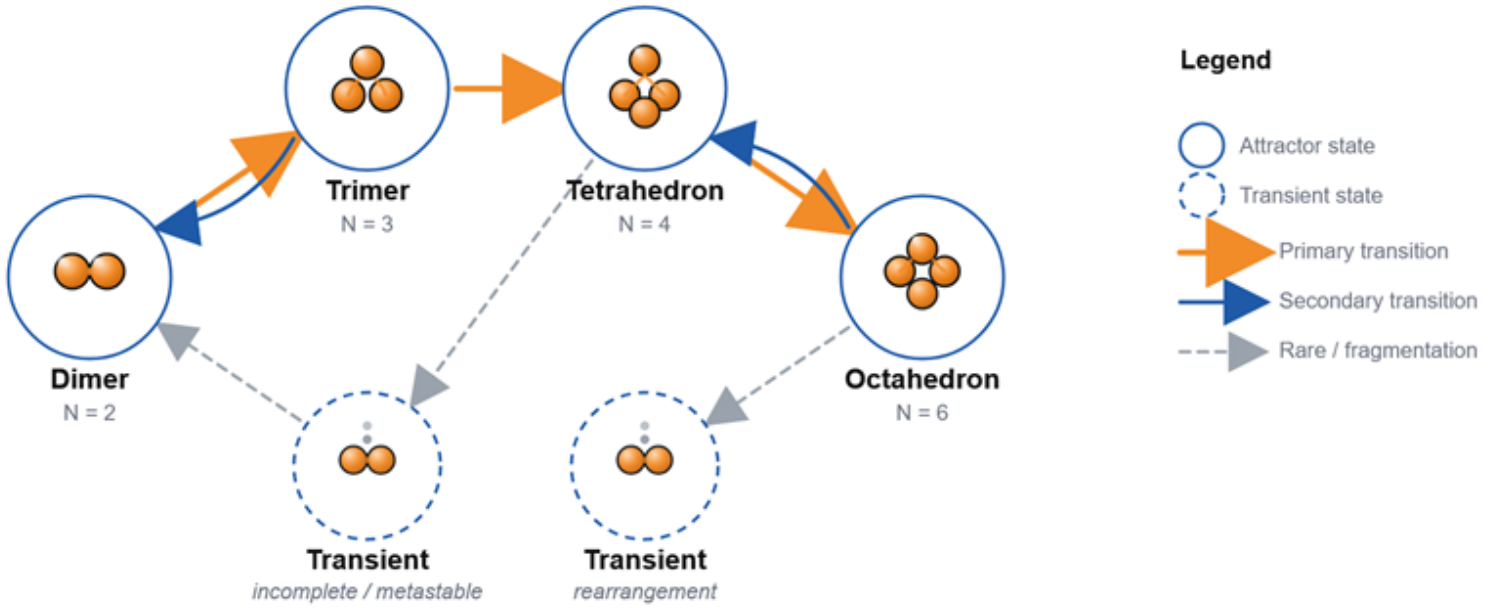
A classical bit is therefore defined by the physical possibility of these tasks.

**Examples of Information Variables for protocells:**

- Geometry G: {monomer, dimer, tetrahedron, octahedron, 13-icosahedron, …}.
- Distance L: discrete near-contact separations set by the CL energy landscape.
- Topology: contact graph / coordination number (bonds).
- Gradients: Δ = {low, high} if reliably created and read.

# Why Clusters qualify as CT information carriers

- **Paper 2**: stable attractors $Z_t$ form discrete macrostates with ordered transitions.
- **Informational closure:** $H(Z_{t+1}|Z_t) \ll H(Z_{t+1}|X_t) \rightarrow$ macrostate is predictive.
- **CT interpretation:** reproducible macrostates support tasks of distinguishing/reading.



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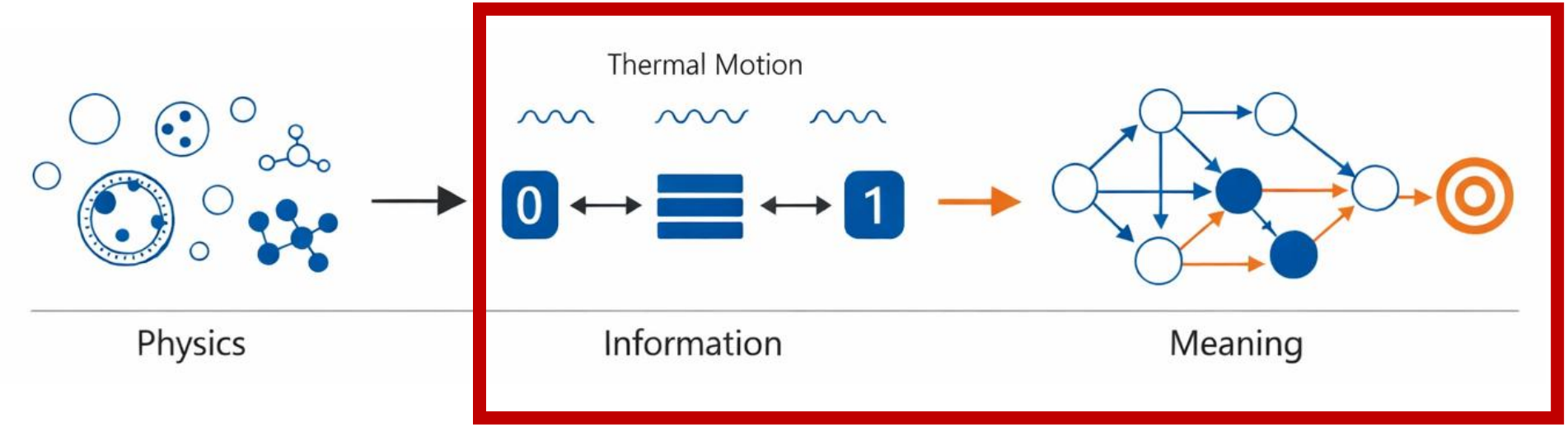


# From Information to Proto-Meaning (1)

**Information** alone does not yet produce **meaning**.

Constructor Theory defines meaning as:
**a reproducible difference that controls which tasks occur.**

If two informational states lead to different downstream transformations,
the difference becomes **functionally meaningful**.

# From Information to Proto-Meaning (2)

Cluster states become **meaningful** when they **control physical processes**.

**Example:**
Dimer configuration ⇒ molecular exchange possible
Isolated protocell ⇒ exchange suppressed

The state therefore selects which tasks the system can perform.

- Information alone ≠ meaning.
- **Meaning** arises when an information value selects different tasks with stable consequences: $x_A \Rightarrow T_A$ and $x_B \Rightarrow T_B$, with $T_A \neq T_B$.

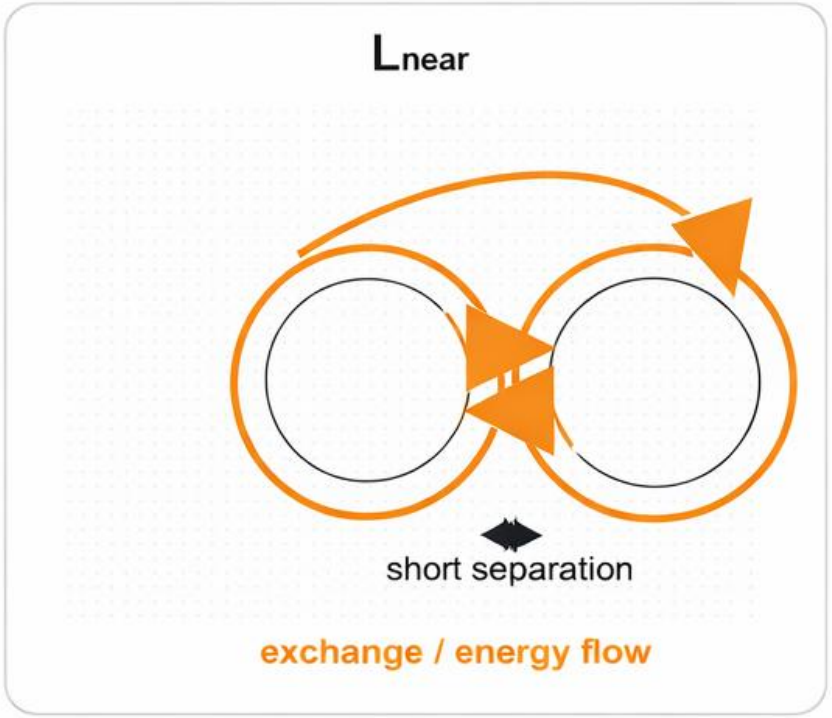
# Distance controls Physics/Function: Intuitive evidence

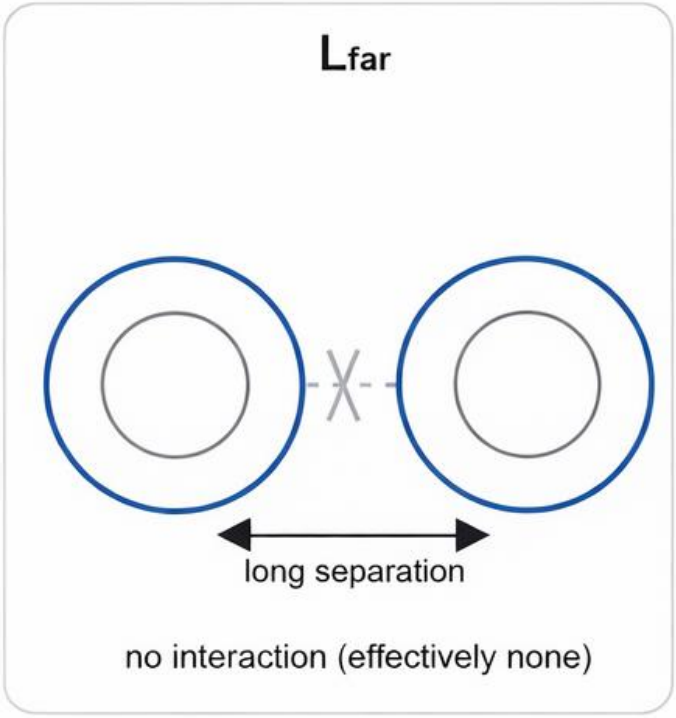
## Purpose

Provide an intuitive mechanism:
distance selects which interactions accur.

## Content

$L_{near}$ vs $L_{far}$ ⟶ different interactions.



# How CT meaning relates to Closure (Rosas et al.)

- **Informational closure:** macrostate predicts the future → supports CT reproducibility.
- **Causal closure:** macro-interventions control transitions → aligns with state-based task gating.
- **Computational closure:** ε-machine exists → provides the minimal rule-level substrate.
- **CT adds:** which states **control tasks** (meaning) vs. merely exist (information).

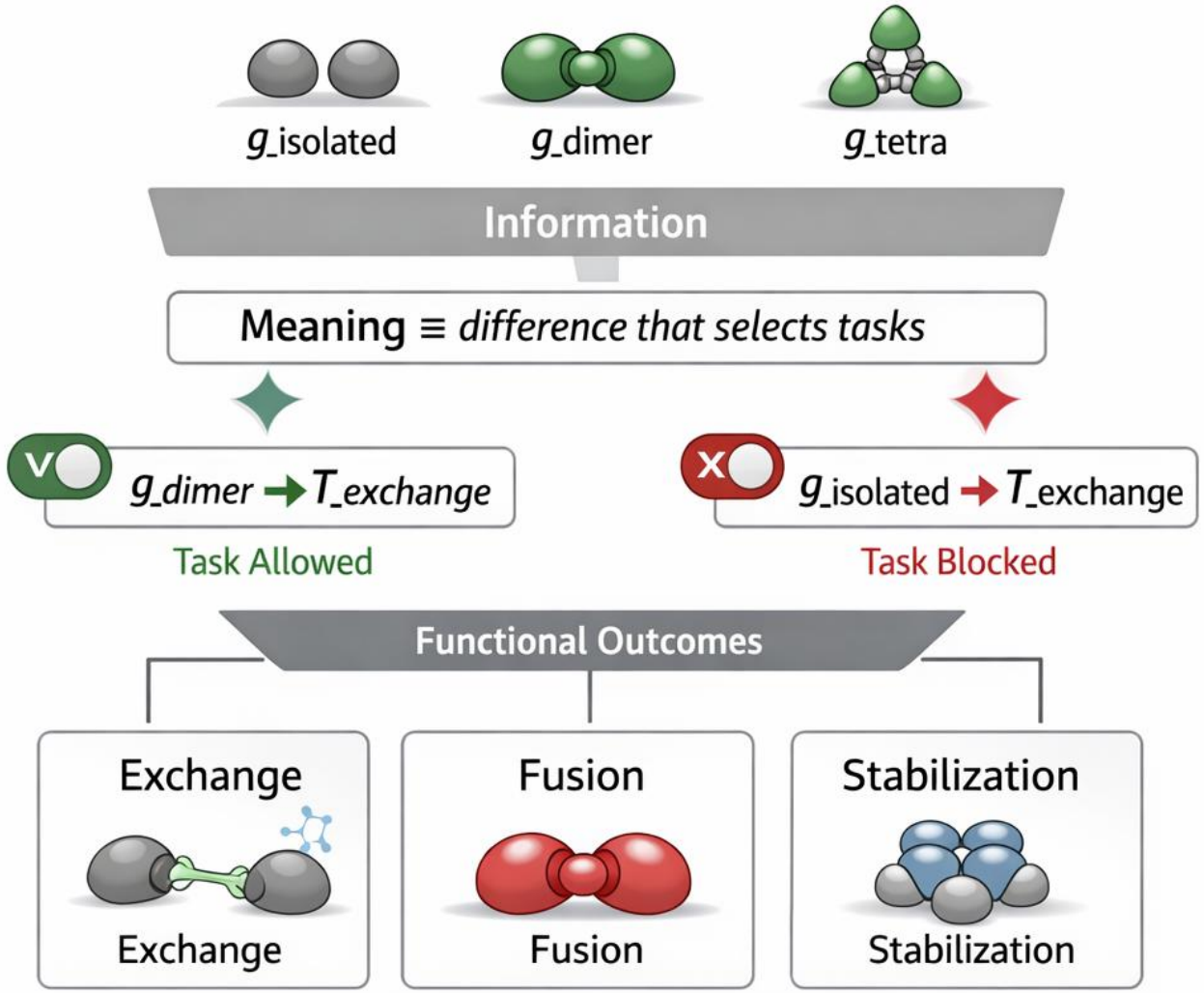
# Protocell clusters as (partial) constructors

- A system is a **constructor** if it can perform tasks repeatedly without being consumed.
- Clusters can repeatedly: **(A)** approach/bind, **(B)** exchange/modify gradients, **(C)** maintain geometry.
- They are '**partial constructors**': rely on environmental resources (temperature, ions) but still gate transformations.

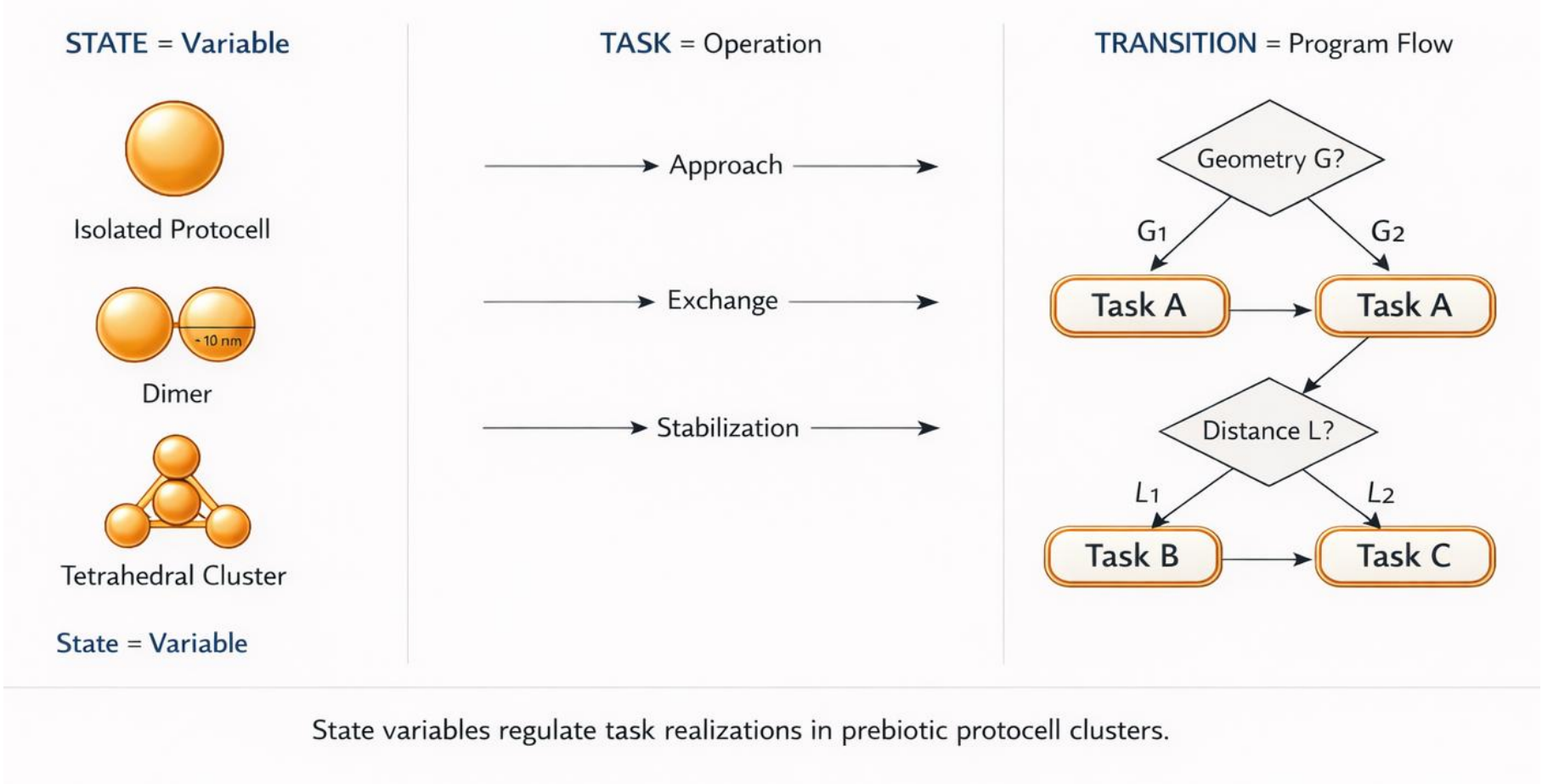
- **Task A** (Approach & bind): isolated → dimer (E_isolated → E_dimer).
- **Task B** (Exchange/transform): Δ_low → Δ'_high within a dimer/cluster.
- **Task C** (Maintenance): restore perturbed geometry back to an attractor (retrieval).
- **Meaning** emerges when task feasibility depends on the information state.

# From information to meaning via task-gating in protocell clusters

- Dimer state enables exchange tasks (ions/molecules) that monomers cannot sustain.
- Near-contact separations enable fusion/hemifusion more readily than far separations.
- Specific geometries can concentrate gradients or stabilize reaction microzones.
- Thus geometry/distance become control variables — meaning in CT sense.

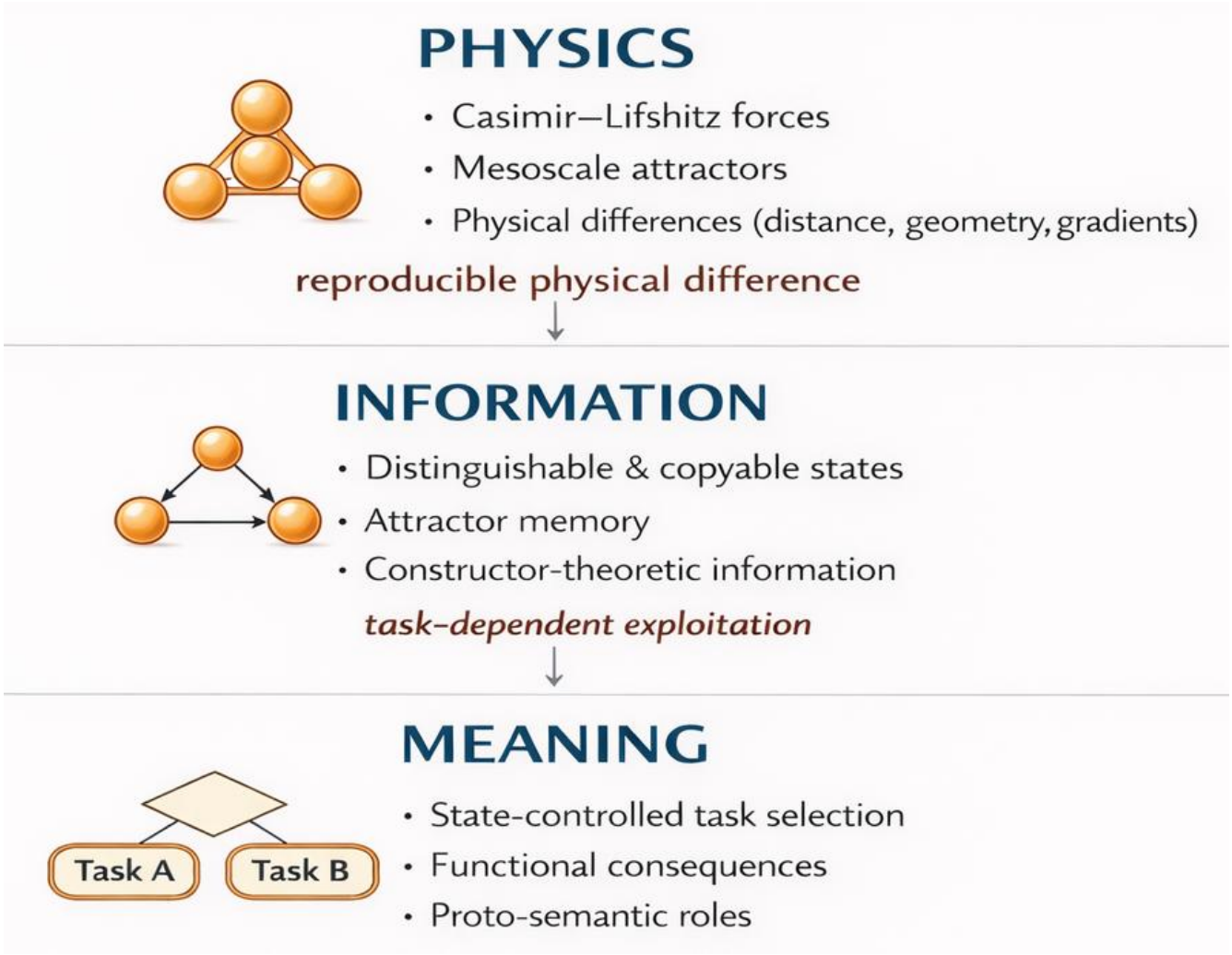


# Proto-Software Architecture in Casimir-Lifshitz-coupled Protocell Clusters




State variables regulate task realizations in prebiotic protocell clusters.

# The Grand Synthesis: From Physics to Meaning




**Meaning** emerges when
**reproducible physical differences systematically control functional tasks**.

# Answering the research questions:

- **RQ1:** Under which physical conditions can protocell clusters act as constructors (repeatable tasks)? - **Physical conditions for protocell constructors**
- Nanoscale separations, dielectric contrast, and moderate ionic strength create **Casimir–Lifshitz interaction landscapes**.
- Stable attractor states enable **repeated tasks** such as approach, coupling, and structural reconfiguration.

# Answering the research questions:

- **RQ2:** How to distinguish informational differences from meaningful states with distinct outcomes? – **From information to meaning**
- **Physical differences** (geometry, distance, ionic gradients) represent information.
- They become **meaningful** when they **control functional outcomes**, e.g., gating fusion, exchange, or cluster stability.

# Answering the research questions:

- **RQ3:** Which task classes support proto-semantic stability and relate to closure/ε-machines? - **Tasks enabling proto-semantic stability**
- Three task classes stabilize clusters: **coupling**, **exchange/transformations**, and **maintenance**.
- These form a **causally** and **informationally closed mesoscale network**, where macro-states determine future dynamics.

# Implications for the Origin of Biological Information

Constructor Theory suggests that **information** can **emerge before genetic polymers**.

Mesoscale physical structures may already support:

- stable informational states
- reproducible transformations
- task-controlled dynamics

Protocell clusters may therefore represent an **early physical basis of biological information**.

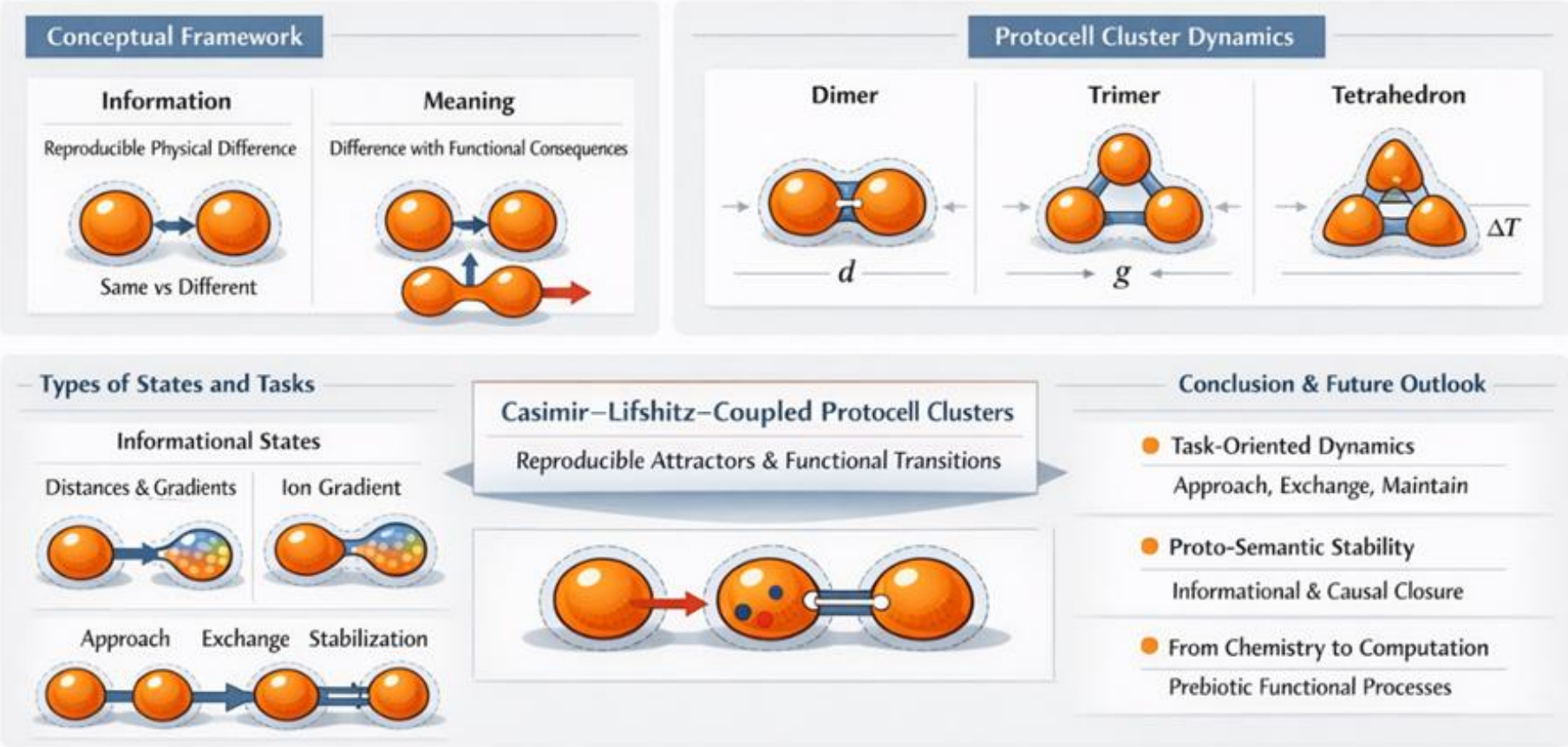
# Take-Home Message:

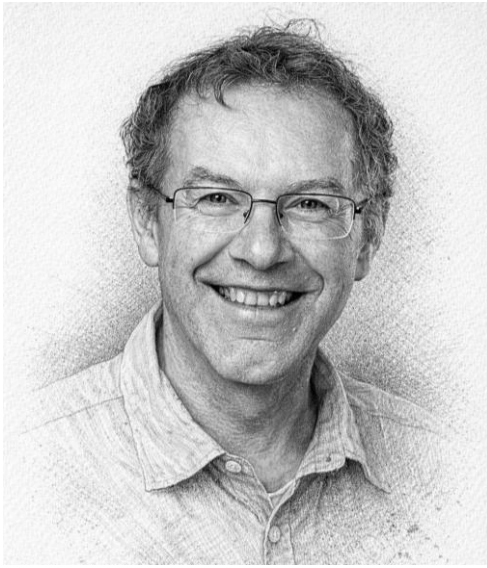
- CT defines information as a reproducible physical difference; clusters provide such differences (attractors).
- Meaning arises when differences gate tasks with stable functional consequences.
- Casimir-Lifshitz-coupled protocell clusters can be treated as **partial constructors** executing repeatable task networks.
- Casimir-Lifshitz-coupled protocell clusters can form **self-stabilizing task networks** that link physical information to **functional organization** — a potential precursor of semantic structure in prebiotic systems.

- **Next step:** Paper 4 — **syntax**, **semantics**, **pragmatics** as layered emergence from the same task architecture.

# Thank you very much for your attention.

# Are there any questions?



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