

## CHEMISTRY

# Enzyme-Inspired Catalysis: Reaction Acceleration Without High Temperature

*How biology drives chemical reactions at ambient conditions*

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convergent strategies	principle clusters	TRL range	featured strategies

**PROBLEM FRAMING**

Industrial catalysis typically requires high temperature and pressure, substantial energy input, and precious metal catalysts. Enzymes achieve the same reactions at ambient conditions with extraordinary specificity — through active site geometry, not brute-force thermodynamics.

Application domains: materials, medicine, energy

Principle cluster: enzymatic catalysis, self organization

## Physics & Mechanism

### Underlying physics

[DRAFT] Enzymes lower activation energy  $\Delta G^\ddagger$  through four mechanisms: (1) Transition state stabilisation — the active site binding site is geometrically complementary to the reaction transition state (not the substrate), reducing entropic barriers. (2) Proximity and orientation — reactant molecules are held in precise orientation, eliminating the entropic cost of collision geometry (effective concentration enhancement of  $10^3$ – $10^6$  M for bimolecular reactions). (3) Electrostatic stabilisation — charged residues stabilise ionic transition states; proton relay networks transfer protons through short, pre-organised pathways. (4) Conformational change — substrate binding induces protein conformational changes that release product from active site ( $k_{cat} > 0$ ) — necessary for catalytic turnover. Rate enhancement: enzymes achieve  $10^3$ – $10^{23}$  fold rate acceleration over uncatalysed reactions. Engineering analogues: metal-organic frameworks (MOFs) with enzymatic active sites achieve  $10^3$ – $10^4$  fold enhancement; cyclodextrin inclusion complexes use geometric confinement; ribozyme-inspired RNA-based catalysts operate in water at physiological conditions. Key challenge: artificial enzymes cannot yet match biological flexibility (multiple substrates) and self-repair capacity. [END DRAFT]

## Biological Strategies

### Catalyze Chemical Breakdown Peptide molecules · TRL 3/9 · 41 genera

Peptide molecules function as programmable chemical catalysts by arranging amino acids in specific sequences that enable precise molecular recognition and targeted action. These peptides self-assemble into nano-scale structures through weak molecular interactions, creating stable yet flexible frameworks. The peptide chains recognize cancer cell markers and bind to them with high specificity. Once ...

**Design principle:** Design multi-functional molecular systems by combining modular building blocks with programmable recognition and catalytic properties. Start by identifying the specific molecular markers or structural

### Chemically Assemble Organic Compounds Bacteria

Bacteria produce polyesters via metabolic pathways that chemically assemble organic monomers into long-chain polymeric structures. These organisms package these polyester compounds, likely into discrete cellular inclusions or granules. Electron microscopy investigations have provided visual evidence of the spatial organization and structural arrangement of these polyester packages within bacterial ...

**Design principle:** The bacterial polyester synthesis and packaging system demonstrates a biological approach to polymer production and storage that could inform industrial polymer manufacturing. Rather than requiring ex

### Catalyze Chemical Breakdown Leafcutter ant · TRL 3/9 · 41 genera ♦ Evidence File

Atta cephalotes, the leafcutter ant, orchestrates chemical breakdown through a sophisticated division of labor and enzymatic strategy. The ants harvest leaf fragments and transport them to underground fungal gardens, where they deposit the leaves as substrate. The ants themselves do not digest the plant material; instead, they cultivate a symbiotic fungus that produces powerful enzymes capable of ...

**Design principle:** Design catalytic systems that leverage ordered molecular assemblies and self-assembling peptide structures to accelerate chemical breakdown in biofilm environments. Surface modification with glycan co

**What's actually hard:** Synthetically replicating the complex multi-organism symbiosis; industrial bioreactors isolate the fungal enzymes but lack the dynamically regulated, vitamin-producing bacterial microbiome that makes the ant's garden highly efficient at ambient tempe...

## Chemically Assemble Mineral Crystals Sponges

Sponges construct their skeletal silica structures via enzymatic catalysis mediated by silicatein, a protein that facilitates the hydrolysis and condensation of silica precursor molecules. That process occurs under mild aqueous conditions at ambient temperature, allowing the organism to build complex three-dimensional mineral architectures with precise control. This silicatein protein acts as a bi...

**Design principle:** Engineers can replicate sponge silica synthesis by designing synthetic peptides that mimic silicatein's catalytic properties. Block copolypeptides containing cysteine and lysine residues can self-orga

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## Coordinate by Self-Organization Multi-enzyme co-localization system · TRL 3/9 · 19 genera

Significant advances in enzyme discovery, protein and reaction engineering have transformed biocatalysis into a viable technology for the industrial scale manufacturing of chemicals. Multi-enzyme catalysis has emerged as a new frontier for the synthesis of complex chemicals. However, the in vitro operation of multiple enzymes simultaneously in one vessel poses challenges that require new strategie...

**Design principle:** Emphasis will be placed on genetically encoded co-localization mechanisms as platforms for future autonomously self-organizing biocatalytic systems. Such genetically programmable systems could be prod

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## EXPLORE THE INTERACTIVE VERSION

This report is a static synthesis. The interactive version includes live strategy cards, the Design Brief generator, Combination Intelligence engine, and filtering by TRL, scale, and principle.

<https://atlasofnature.org/challenge/enzyme-inspired-catalysis>

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