AL-FARABI KAZAKH NATIONAL UNIVERSITY FACULTY OF BIOLOGY AND BIOTECHNOLOGY DEPARTMENT OF BIOTECHNOLOGY

INTRODUCTION TO BIOLOGICAL ENGINEERING

LECTURE 2.
BIOLOGICAL SYSTEMS AS ENGINEERING OBJECTS: CELLS, MICROORGANISMS, AND BIOLOGICAL MATERIALS IN BIOTECHNOLOGY

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Lecture Plan

1. What makes a biological system engineerable
2. Cells as dynamic systems
3. Microorganisms as production hosts
4. Mammalian and plant cells
5. Biological materials and matrices
6. Genotype–phenotype relationships
7. Resource allocation and burden
8. Environmental interactions
9. Selection of an engineering object
10. Case studies and student tasks

Learning Objectives

By the end of this lecture, students should be able to:

- Describe cells, microorganisms and biological materials as engineering objects.
- Identify biological properties that support or constrain engineering design.
- Compare common microbial and eukaryotic production hosts.
- Explain genotype–phenotype, resource allocation and environment–system interactions.
- Select an appropriate biological chassis for a defined application.
- Recognize why materials derived from biology require characterization across multiple scales.

What is an “engineering object”?

An engineering object is a system that can be described in terms of structure, function, operating conditions and measurable performance, and whose behaviour can be intentionally analysed, controlled or modified to achieve a defined objective.

Biological systems are unusual engineering objects because they are **dynamic, adaptive and context-dependent**. Cells and tissues grow, respond to environmental signals, reorganize their internal state and may evolve over time. Consequently, the same intervention may produce different outcomes under different biological or operating conditions.

An engineering object may therefore be:

- a **molecule or enzyme**, when catalytic activity or binding is being optimized;
- a **cell or microbial population**, when metabolism, growth or gene expression is controlled;
- a **tissue or biomaterial**, when mechanics, transport or biocompatibility are important;
- a **bioreactor or microbial community**, when system-level performance, stability and scale become the primary concern.

Engineering analysis begins by defining three elements:

Function — What should the system accomplish?

Controllable variables — Which properties or operating conditions can be changed?

Constraints — Which biological, physical or regulatory limitations cannot be ignored?

The appropriate engineering object is therefore defined not only by what the biological system is, but by the question being asked and the performance that must be achieved.

Cells as open systems

Cells are open, non-equilibrium systems that continuously exchange matter, energy and information with their environment. Their internal state is maintained through coordinated transport, metabolism and regulation rather than through thermodynamic equilibrium.

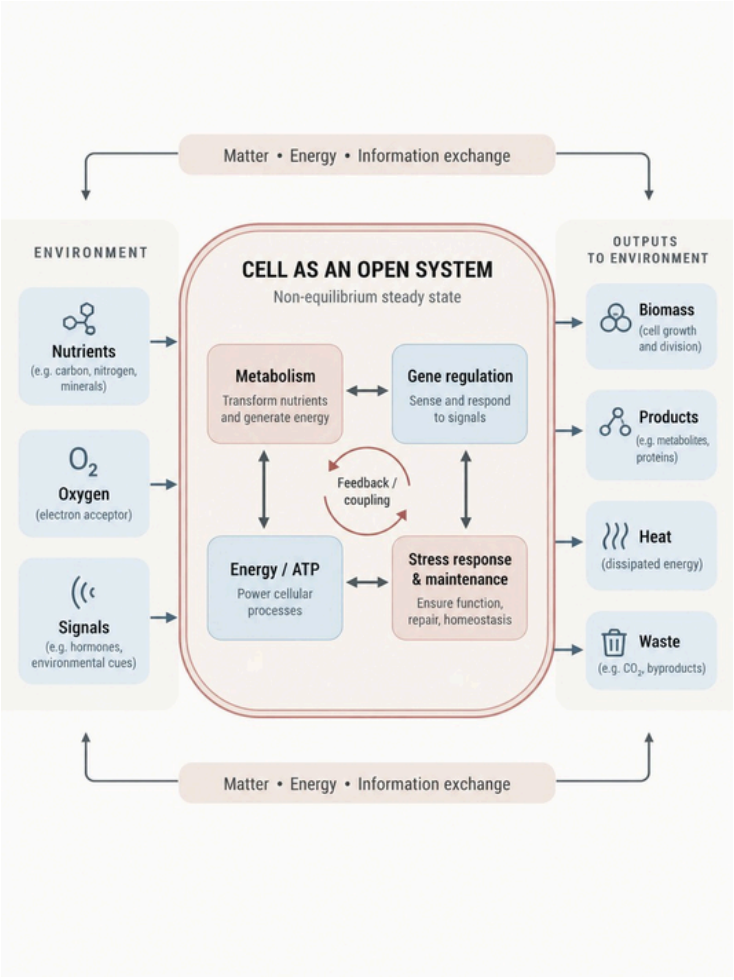
Matter exchange: nutrients, water, ions and gases enter the cell, while metabolites, products and waste are released.

Energy conversion: chemical energy is transformed into ATP, reducing equivalents and biosynthetic capacity required for growth and maintenance.

Information exchange: extracellular signals alter gene expression, metabolism and cellular behaviour.

Cellular resources are limited; therefore, increasing one engineered function may redistribute **energy, ribosomes, metabolites and regulatory capacity** away from native processes.

Because cells respond dynamically to their environment, engineering performance depends strongly on **physiological state and operating conditions**.



Cellular architecture and function

Cellular architecture determines where biological reactions occur, how molecules are transported, and how efficiently proteins and metabolites are synthesized, processed and secreted. For biological engineering, these structural differences directly influence host selection, product quality and process performance.

Prokaryotic cells

- Lack membrane-bound organelles and often couple **transcription and translation**, enabling rapid growth and fast genetic manipulation.
- Their relatively simple architecture supports efficient production of many enzymes, metabolites and recombinant proteins.
- Limitations include restricted **post-translational modification, protein folding and secretion** for some complex products.

Eukaryotic cells

- Use intracellular compartmentalization, including the **nucleus, endoplasmic reticulum and Golgi apparatus**, to separate and regulate cellular functions.
- They support complex protein folding, secretion and post-translational modifications required for many therapeutic proteins.
- Their cultivation is generally **slower, more demanding and more sensitive to environmental conditions**.

Engineering relevance
Cellular architecture affects product localization, transport limitations, metabolic burden, folding efficiency and secretion capacity. Therefore, the optimal host is selected according to the biological function and quality requirements of the final product—not simply according to growth rate.

Microorganisms as cell factories

Microbial cell factories are engineered microorganisms whose metabolic and regulatory networks are redirected toward the efficient production of a desired compound. Bacteria and yeasts are widely used because they grow rapidly, can reach high cell densities and are relatively accessible to genetic and process engineering.

Microbial platforms are used to manufacture **enzymes, amino acids, vitamins, organic acids, recombinant proteins, biofuels and specialty chemicals**.

Production can be improved by **increasing precursor supply, removing competing pathways, balancing cofactors and enhancing product export**.

Strain engineering must consider **metabolic burden**: excessive expression can reduce growth, alter resource allocation and decrease long-term productivity.

Industrial performance depends not only on product formation, but also on **genetic stability, substrate utilization, oxygen demand, product toxicity and downstream recovery**.

The optimal strain therefore represents a balance between **growth, yield, productivity, robustness and manufacturability**.

Escherichia coli: strengths and limits

Escherichia coli is one of the most widely used microbial hosts in biological engineering because it combines rapid growth, well-characterized genetics and high recombinant expression capacity. However, its suitability depends strongly on the type of product and the required quality attributes.

- **Major strengths:** short doubling time, inexpensive cultivation, extensive genetic tools, high cell-density fermentation and strong recombinant protein expression.
- **Major limitations:** endotoxin formation, limited eukaryotic post-translational modifications, inclusion-body formation, acetate overflow and restricted secretion of some recombinant proteins.
- **Process sensitivity:** productivity and product quality depend on strain background, promoter strength, plasmid copy number, induction strategy, temperature, oxygen availability and feeding regime.
- **Engineering trade-off:** maximizing expression can increase metabolic burden, reduce growth and promote misfolding or by-product formation.

Why choose E. coli?

Best suited for:
enzymes • research proteins • metabolic products • simple recombinant proteins

Less suitable for:
complex glycoproteins • proteins requiring extensive PTMs • products highly sensitive to endotoxin contamination

Host selection principle:
The most productive host is not necessarily the best host; selection should balance **expression level, product quality, process robustness, purification burden and regulatory requirements**.

Yeasts as engineering hosts

Yeasts combine the genetic accessibility of microorganisms with important eukaryotic capabilities such as protein folding, secretion and post-translational processing. This makes them valuable hosts for recombinant proteins, enzymes, metabolites and lipid-derived products.

- **Saccharomyces cerevisiae** is well characterized, robust and widely used industrially. It is suitable for metabolic engineering and production of proteins, fuels and chemicals.
- **Komagataella phaffii** is particularly attractive for **high-cell-density cultivation and recombinant protein secretion**, but performance strongly depends on oxygen transfer and expression conditions.
- **Yarrowia lipolytica** has a strong capacity for **lipid metabolism**, making it useful for production of fatty acids, oleochemicals and other hydrophobic compounds.
- Important engineering constraints include **glycosylation patterns, secretion bottlenecks, oxygen demand, metabolic burden and product toxicity**.

Host	Engineering advantage	Typical limitation
S. cerevisiae	Robust genetics and industrial history	Crabtree effect; product-dependent secretion limits
K. phaffii	High-density growth and strong protein secretion	High oxygen demand; expression conditions require careful control
Y. lipolytica	Strong lipid and acetyl-CoA metabolism	More specialized genetic/process optimization

Mammalian cells

Mammalian cells are the preferred production hosts for complex therapeutic proteins that require human-like folding, assembly and post-translational modifications. Their ability to generate clinically relevant glycosylation patterns makes them especially important for monoclonal antibodies and other biologics.

CHO cells are the dominant industrial platform because of their long regulatory history, adaptability to suspension culture and suitability for large-scale manufacturing.

Mammalian cells grow more slowly than microbial hosts and require **complex media, strict sterility and carefully controlled culture conditions**.

Product quality is strongly linked to cell physiology; changes in **pH, temperature, nutrient availability and dissolved oxygen** can alter glycosylation, aggregation and charge variants.

High productivity must therefore be balanced with **cell viability, product quality, process consistency and downstream purification requirements**.

WHY USE MAMMALIAN CELLS?

Complex product requirements

- Correct protein folding
- Disulfide bond formation
- Human-like glycosylation
- Efficient secretion

Engineering constraints

- Slow growth
- High media cost
- Shear sensitivity
- Strong process dependence

ENGINEERING PERSPECTIVE

Mammalian-cell bioprocessing is a clear example of how **host biology and process conditions jointly determine final product quality**. The objective is not simply to maximize protein concentration, but to maintain the required quality attributes throughout cultivation and scale-up.

Plant cells and whole plants

Plant platforms provide distinctive opportunities for biological engineering because they combine diverse biosynthetic capacity with cellular compartmentation and scalability at the organism level.

- **Plant cell cultures** offer relatively controlled production environments and are useful for recombinant proteins, specialized metabolites and research-scale bioprocessing.
- **Whole plants** enable tissue-specific expression and agricultural-scale biomass production, making them attractive for food, molecular farming and sustainable materials.
- Their main advantages include access to **unique metabolic pathways**, reduced dependence on animal-based systems and relevance to applications in agriculture, health and bio-based manufacturing.
- Important limitations include **slower development cycles, biological heterogeneity, complex downstream recovery and regulatory challenges**, especially for open-field or environmental use.

Engineering perspective

In plant engineering, the choice between **cell culture and whole-plant systems** depends on the target product, required control level, scale of production and the difficulty of product extraction and purification.

Cell-free biological systems

Cell-free systems use extracted or reconstituted biological machinery outside living cells to perform transcription, translation and biochemical synthesis. By removing the requirement to maintain cell growth and viability, they provide a highly controllable platform for rapid prototyping and biochemical production.

Reaction composition can be **directly manipulated**, including DNA templates, enzymes, substrates, cofactors and energy systems.

Cell-free platforms are especially useful for **rapid design–test cycles, biosensing, pathway prototyping and production of compounds that may be toxic to living cells**.

Miniaturization enables **high-throughput screening** and parallel testing of many genetic or metabolic designs.

Key limitations include **reagent cost, limited reaction lifetime, cofactor and energy regeneration, and challenges associated with large-scale production**.

Why use a cell-free platform?

Advantages

Precise control of reaction composition
No requirement for cell viability
Rapid prototyping
Access to toxic or non-natural products
High-throughput compatibility

Engineering constraints

Energy regeneration
Reaction stability
Reagent cost
Product recovery
Scale-up

Microbial communities

Microbial communities consist of interacting populations whose collective behaviour can differ substantially from that of the individual strains. In engineered consortia, different species or strains can divide metabolic tasks, exchange intermediates and perform functions that are difficult to achieve with a single organism.

Division of labour allows complex pathways to be distributed between specialized populations, reducing the metabolic burden placed on any one strain.

Cross-feeding links community members through the exchange of metabolites, nutrients or signalling molecules.

Community performance depends on **population ratios, resource competition, spatial organization and environmental conditions**.

Cooperative interactions can improve robustness, but excessive dependence may reduce stability when one population declines or operating conditions change.

Engineering therefore requires measurements at both the **single-strain and community levels**, including composition, interaction strength, productivity and temporal stability.

Engineering an artificial consortium

Strain A

Substrate → Intermediate

↓ cross-feeding

Strain B

Intermediate → Target product

Под схемой:

Key design variables: population ratio •metabolite exchange • growth compatibility • spatial organization • stability

Genotype to phenotype

Genotype defines the biological potential of a system, but phenotype emerges from the interaction between genetic information, regulatory networks, cellular state and environmental conditions. Therefore, identical genetic constructs can produce different functional outcomes in different biological contexts.

Gene expression depends on **promoter activity, copy number, genomic location and regulatory interactions**.

Cellular phenotype is further shaped by **metabolic state, growth rate, nutrient availability, stress and previous environmental history**.

The same engineered construct may therefore behave differently across **hosts, media, temperatures or cultivation conditions**.

These context effects limit the assumption that biological parts are fully modular and transferable.

Engineering decisions must be based on **experimental characterization in the intended host and operating environment**, rather than on sequence information alone.

Genotype
DNA sequence • regulatory elements • copy number

↓

Cellular context
Regulation • metabolism • resource availability • environment

↓

Phenotype
Growth • expression • morphology • productivity • stress response

Resource allocation and burden

Engineered gene expression competes with native cellular functions for a finite pool of resources. Ribosomes, ATP, amino acids, membrane capacity, chaperones and metabolic precursors must be shared between growth, maintenance and production of the engineered function.

High heterologous expression can create **metabolic and translational burden**, reducing growth and altering host physiology.

Excessive burden may activate stress responses, decrease productivity and favour mutants that weaken or eliminate the engineered construct.

Burden is influenced by **promoter strength, gene copy number, induction timing, protein folding demand and product toxicity**.

Increasing expression therefore does not always increase useful product formation; beyond an optimum, additional expression may reduce overall system performance.

Resource-aware design balances cellular capacity with production demand to improve productivity, robustness and long-term genetic stability.

Evolution as a design variable

Evolution continuously modifies engineered biological systems through mutation, selection and population dynamics. During long cultivations or repeated passages, variants with higher fitness can gradually replace the original engineered population, especially when the desired function imposes a metabolic or regulatory burden.

- Engineered traits that reduce host fitness are vulnerable to **mutation, deletion, silencing or loss of expression** over time.
- Evolutionary stability depends on **mutation rate, selection pressure, population size, genetic architecture and the fitness cost of the engineered function**.
- Designs can be stabilized by reducing metabolic burden, integrating constructs into the genome and coupling the desired function to cellular fitness.
- Evolution can also be used deliberately through **adaptive laboratory evolution (ALE)** to improve substrate utilization, stress tolerance or growth under defined conditions.
- Long-term performance should therefore be evaluated across **multiple generations**, not only in short-term experiments.

Evolution as a challenge

Mutation → loss of function → reduced productivity → population takeover

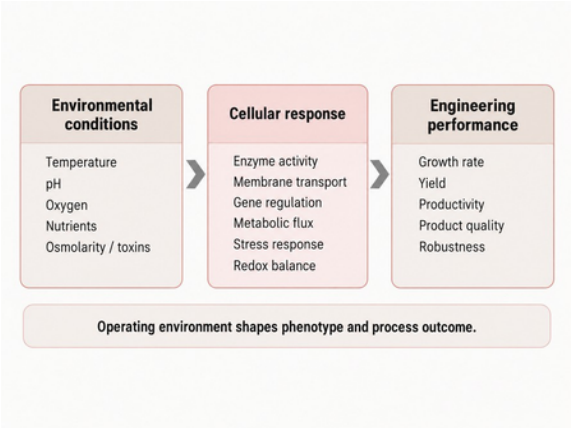
Evolution as a tool

Variation → selection → enrichment → improved phenotype

Environmental sensitivity

Biological systems are highly sensitive to their operating environment. Temperature, pH, oxygen availability, osmolarity and nutrient supply directly influence enzyme activity, membrane transport, redox balance, gene expression and metabolic fluxes.

- **Temperature** affects reaction rates, protein stability and membrane properties.
- **pH** influences enzyme activity, transport processes and intracellular energy balance.
- **Oxygen availability** alters respiration, redox state and pathway utilization.
- **Nutrient concentration and feeding strategy** determine growth rate, overflow metabolism and product formation.
- Osmotic stress and toxic compounds can trigger **stress responses**, redirecting cellular resources away from production.



Engineering perspective

The same engineered strain may show very different performance under different operating conditions. Therefore, environmental variables should be treated as **controlled process parameters** and linked directly to measurable outputs such as growth, productivity, yield and product quality.

Biological materials as engineering objects

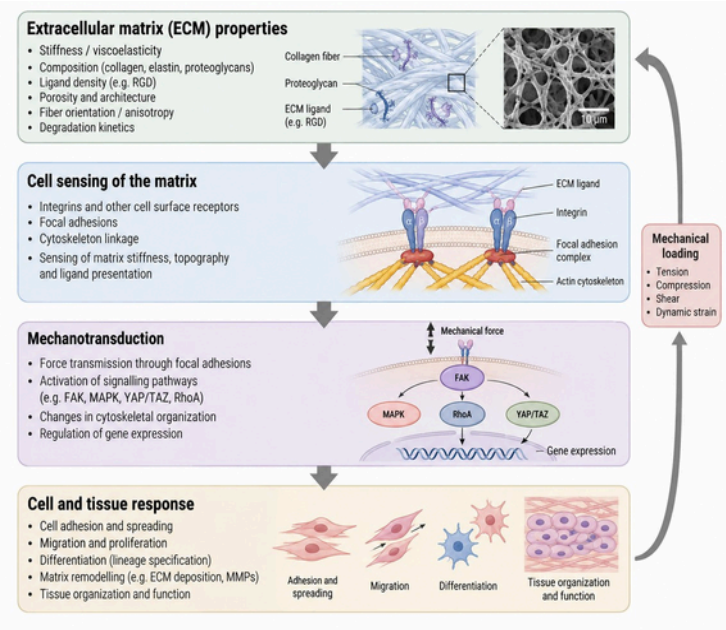
Biological materials are engineered through the relationship between composition, structure, physical properties and biological response. Their performance cannot be predicted from chemistry alone because function often emerges from hierarchical organization across multiple length scales.

- Biological materials may be **natural, synthetic or hybrid**, including collagen, cellulose, silk, alginate, chitosan and engineered living materials.
- Their behaviour depends on **composition, microstructure, porosity, stiffness, surface chemistry and degradation kinetics**.
- Material properties regulate **cell adhesion, migration, differentiation, transport of nutrients and interaction with surrounding tissues or microorganisms**.
- Hierarchical organization—from molecular assembly to macroscopic architecture—can generate mechanical and biological properties that are not evident from the individual components.
- Engineering therefore requires linking **material structure and measurable properties to the intended biological function**.

Extracellular matrix and tissue mechanics

The extracellular matrix (ECM) is a dynamic structural and biochemical environment that regulates cell behaviour through mechanical, spatial and molecular cues. Cells sense matrix properties through adhesion receptors and mechanotransduction pathways, converting physical signals into changes in cytoskeletal organization, gene expression and phenotype.

- **Matrix stiffness and viscoelasticity** influence cell spreading, migration, proliferation and differentiation.
- **Ligand density and biochemical composition** regulate cell adhesion and receptor-mediated signalling.
- **Porosity, fiber orientation and anisotropy** control transport, spatial organization and direction-dependent mechanical behaviour.
- Mechanical loading such as **tension, compression and shear** can remodel both cells and the surrounding matrix.
- Engineered scaffolds therefore aim to reproduce the **critical functional cues** of native ECM rather than its complete complexity.



Transport across biological boundaries

Transport processes determine whether nutrients, gases, signaling molecules, drugs and metabolites can reach their site of action at the required rate. In biological systems, transport is governed by concentration gradients, membrane permeability, carrier kinetics, convection and characteristic diffusion distance.

Passive diffusion is driven by concentration gradients and depends on diffusivity, membrane properties and path length.
Carrier-mediated transport enables selective uptake but may become saturated at high substrate concentrations.
Convection and perfusion become increasingly important at tissue and reactor scales, where diffusion alone may be insufficient.

Transport resistance can generate **oxygen, nutrient or drug gradients**, producing heterogeneous cellular states within the same system.

At larger size or higher cell density, transport limitations often become the dominant constraint on biological performance.

TRANSPORT MECHANISMS
Diffusion
Concentration gradient → molecular movement **Facilitated / active transport**
Membrane proteins → selective uptake **Convection / perfusion**
Bulk fluid flow → long-range transport
↓
Engineering consequence
Gradients • local depletion • heterogeneous response • reduced performance

Choosing a chassis: decision criteria

Chassis selection is a multi-criteria engineering decision. The optimal host is not simply the fastest-growing or most familiar organism, but the one that best satisfies the biological, process, product-quality and regulatory requirements of the application.

- **Growth and cultivation:** growth rate, achievable cell density, substrate utilization and media cost.
- **Genetic tractability:** availability of vectors, genome-editing tools, stable expression systems and characterized regulatory parts.
- **Product capability:** secretion efficiency, folding, post-translational modification and tolerance to toxic products.
- **Process compatibility:** oxygen demand, shear sensitivity, robustness and suitability for scale-up.
- **Downstream processing:** intracellular versus secreted product localization can strongly influence purification complexity and cost.
- **Regulatory and safety considerations:** prior industrial use, endotoxin or contaminant risks and regulatory history may affect host suitability.

Criterion	E. coli	Yeast	Mammalian cells
Growth rate	High	Moderate–high	Low
Genetic tractability	Excellent	Excellent	Moderate
Complex PTMs	Limited	Moderate	Excellent
Secretion	Limited	Good	Good
Process cost	Low	Moderate	High
Regulatory history	Strong	Strong	Very strong for biologics

Comparison matrix for production hosts

Production host	Growth / cultivation	Genetic engineering	Protein processing / PTMs	Main advantages	Main limitations
Bacteria (E. coli)	Very rapid; inexpensive media	Excellent	Limited	High expression, simple scale-up, low cost	Endotoxin, inclusion bodies, limited complex PTMs
Yeasts	Rapid; robust fermentation	Excellent	Moderate; species-dependent glycosylation	Secretion, eukaryotic folding, industrial robustness	Non-human glycosylation, oxygen demand, secretion bottlenecks
Mammalian cells (CHO)	Slow; complex and costly	Moderate–high	Excellent; human-like	Preferred for antibodies and complex biologics	High cost, long process times, contamination sensitivity
Plant systems	Slow development; scalable biomass	Moderate	Complex, but plant-specific	Molecular farming, specialized metabolism, low-cost biomass	Heterogeneity, downstream recovery, regulatory constraints
Cell-free systems	No cell growth required	Highly controllable	System-dependent	Rapid prototyping, toxic products, high-throughput testing	Reagent cost, limited lifetime and scale

Case study: insulin versus monoclonal antibody

The molecular requirements of the target product strongly influence host selection. Recombinant insulin and monoclonal antibodies illustrate two very different production strategies.

Recombinant insulin

- Relatively small protein with **no requirement for complex glycosylation**.
- Can be produced efficiently in **microbial hosts such as *E. coli* or yeast**.
- Main engineering priorities include expression level, correct processing, folding, recovery and purification.
- Microbial production enables **rapid growth, high productivity and comparatively low manufacturing cost**.

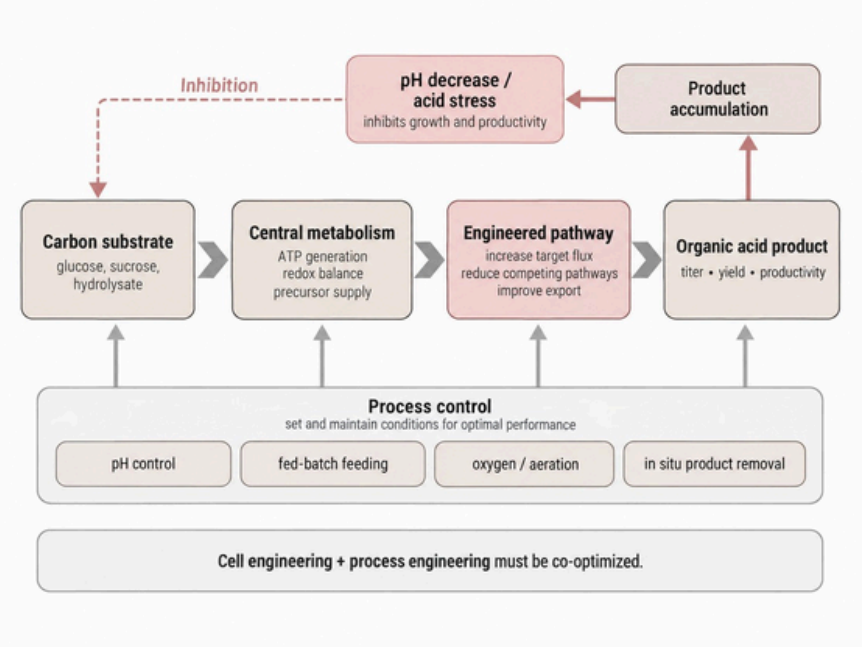
Monoclonal antibody

- Large, structurally complex glycoprotein composed of multiple polypeptide chains.
- Requires correct **folding, disulfide-bond formation, assembly and glycosylation**.
- Mammalian cells, particularly **CHO cells**, are therefore widely used to achieve appropriate product quality.
- Key process priorities include cell viability, glycan profile, aggregation, product consistency and sterility.

Case study: microbial organic-acid production

Microbial production of organic acids requires coordinated control of carbon flux, cellular energetics and product tolerance. A high-performing strain must redirect substrate toward the target acid while maintaining sufficient ATP generation, redox balance and precursor supply for growth and maintenance.

- Carbon flux can be increased by **amplifying the desired pathway, removing competing reactions and improving precursor availability**.
- Product accumulation often lowers extracellular pH and may inhibit growth, membrane function and metabolic activity.
- High titer therefore requires not only pathway engineering, but also sufficient **acid tolerance and export capacity**.
- Process variables such as **pH, substrate concentration, oxygen supply and feeding strategy** strongly influence yield and productivity.
- Cell engineering and process engineering should be optimized together because the best-performing strain under one operating condition may perform poorly under another.



Measurement of biological objects

Biological engineering depends on measurements that convert complex system behaviour into quantitative variables. The choice of method should match the biological scale, the property of interest and the engineering decision that must be made.

- **Optical density (OD)** provides a rapid estimate of biomass concentration, but becomes nonlinear at high cell densities and cannot distinguish viable from non-viable cells.
- **Flow cytometry** measures single-cell properties and reveals population heterogeneity that is hidden by bulk averages.
- **Microscopy** provides information on morphology, spatial organization, localization and cell–material interactions.
- **Omics and metabolite profiling** characterize internal molecular states, pathway activity and metabolic responses.
- No single method captures the complete state of a biological system; reliable analysis often requires **complementary measurements across multiple scales**.

Measurement method	What it measures	Main limitation
Optical density	Bulk biomass	No viability or single-cell information
Flow cytometry	Single-cell distributions	Requires suitable markers / sample preparation
Microscopy	Morphology & spatial organization	Limited throughput
Omics	Molecular state	High dimensionality and complex interpretation
Metabolite analysis	Metabolic activity	Often requires destructive sampling

Failure modes in engineered cells

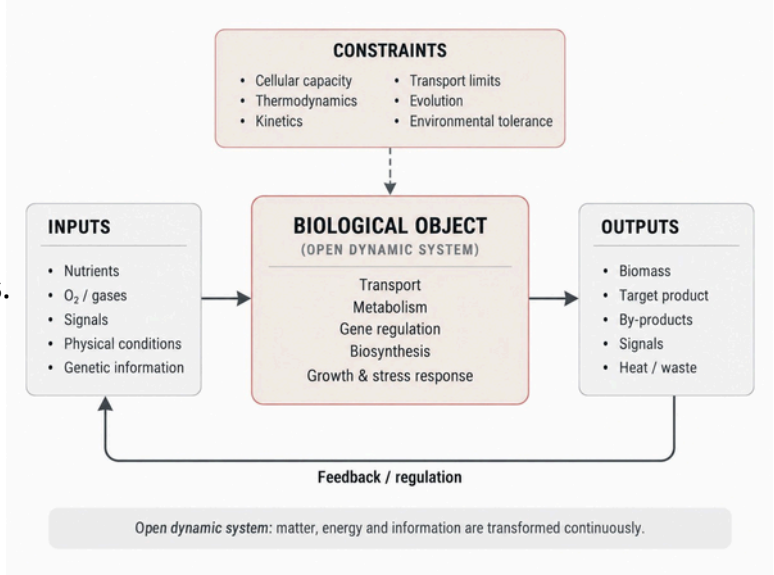
Engineered cells may lose performance when genetic stability, metabolic balance, cellular resources or environmental conditions are disrupted. Failure analysis should therefore identify both the immediate phenotype and the underlying mechanism.

- **Genetic failure:** plasmid loss, mutation or recombination can reduce or eliminate expression of the engineered function.
- **Metabolic failure:** pathway imbalance may deplete precursors or cofactors, accumulate toxic intermediates and increase unwanted by-products.
- **Physiological failure:** excessive expression burden can trigger stress responses, proteolysis, growth inhibition or cell death.
- **Transport failure:** insufficient uptake, secretion or intracellular transport can limit substrate delivery or product removal.
- **Process-related failure:** oxygen limitation, pH shifts, nutrient gradients or measurement errors may produce apparent biological failure even when the genetic design is intact.

Systems view of a biological object

A biological object should be analysed as an open, dynamic system in which material, energy and information are continuously transformed. Its behaviour emerges from the interaction between internal biological processes and external operating conditions.

- **Inputs** include nutrients, gases, physical conditions, regulatory signals and genetic information.
- **Internal processes** include transport, metabolism, gene regulation, biosynthesis, growth, repair and stress responses.
- **Outputs** may include biomass, target product, by-products, signals, heat and waste streams.
- **Constraints** arise from cellular capacity, thermodynamics, kinetics, transport limitations, evolutionary stability and environmental tolerance.
- **Feedback** links system performance back to regulation and process control, allowing the biological state to change dynamically over time.



Engineering rule: context is part of the object

A biological object cannot be characterized independently of the conditions in which it operates. Measured performance emerges from the interaction between the intrinsic properties of the system and its environmental, process and measurement context.

- A microbial strain should be described together with its **medium composition, temperature, pH, oxygen availability, reactor configuration and cultivation mode**.
- A biomaterial should be evaluated under defined **hydration, mechanical loading, sterilization and biological exposure conditions**.
- The same biological system may therefore show different growth, productivity, mechanical behaviour or stability when the surrounding conditions change.
- Measurement methods are also part of the context: different assays may capture different aspects of the same biological state.
- Performance claims should always specify the **conditions, scale and measurement method** under which they were obtained.

SYSTEM PROPERTIES
Genotype • material composition • architecture
+
OPERATING CONTEXT
Medium • pH • temperature • O_2 • loading • scale
+
MEASUREMENT CONTEXT
Method • sampling • resolution • calibration
↓
OBSERVED PERFORMANCE
Growth • productivity • mechanics • stability • quality

Student Tasks

Define the system boundary for one biological engineering example and justify why that boundary is appropriate.

Draw an input–process–output or conceptual model and label the most important flows and interactions.

Identify three performance metrics and two important constraints for the selected system.

Describe one plausible failure mode and propose one engineering control or design improvement. Find one recent peer-reviewed article relevant to the lecture topic and summarize the engineering contribution in 3–4 sentences.

Selected References and Further Reading

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