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

INTRODUCTION TO BIOLOGICAL ENGINEERING

LECTURE 4.
MAIN DIRECTIONS OF BIOLOGICAL ENGINEERING: BIOTECHNOLOGY, BIOPROCESS, BIOMEDICAL, AND ENVIRONMENTAL APPLICATIONS

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Lecture Plan

1. Biomanufacturing
2. Bioprocess engineering
3. Synthetic and metabolic engineering
4. Biomedical engineering
5. Tissue engineering and biomaterials
6. Biosensors and diagnostics
7. Agricultural applications
8. Environmental engineering biology
9. Sustainability and circular bioeconomy
10. Translation and case studies

Learning Objectives

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

- Identify the major application domains of biological engineering.
- Compare engineering goals and performance metrics across domains.
- Explain how biological and process design interact in biomanufacturing.
- Describe biomedical and environmental examples of engineering biology.
- Recognize domain-specific constraints in regulation, scale, safety and sustainability.
- Analyze a real application using system-level engineering logic.

A field organized by problems, not borders

- Biological engineering is unified by engineering logic but diversified by application goals.
- The same tools—modelling, measurement, design, control and optimization—appear in manufacturing, medicine, agriculture and the environment.



Differences arise from context: industrial reactors prioritize productivity, medical systems prioritize patient safety, and environmental systems face open ecosystems.

Understanding these contexts prevents inappropriate transfer of design assumptions from one domain to another.

TERMS system boundary • mechanism • constraint• performance metric

Teaching focus: connect “A field organized by problems, not borders” to a measurable engineering decision. Ask which variable should be measured first, what assumption is most fragile, and how the conclusion would change at a different scale.

Biomanufacturing

ENGINEERING LENS

Define → Measure → Model → Compare → Improve

- Biomanufacturing uses cells, enzymes or cell-free systems to convert feedstocks into products at useful scale and quality.
- Products include biologics, vaccines, enzymes, food ingredients, chemicals, fuels and materials.
- Key metrics include titer, yield, productivity, product quality, batch consistency and cost of goods.
- Biological design and process design must be integrated because host physiology depends strongly on operating conditions.

TERMS system boundary • mechanism • constraint• performance metric

Teaching focus: connect “Biomanufacturing” to a measurable engineering decision. Ask which variable should be measured first, what assumption is most fragile, and how the conclusion would change at a different scale.

Bioprocess engineering

System

Bioprocess engineering converts biological activity into controlled, scalable unit operations.

Mechanism

Upstream operations include inoculum, media preparation and cultivation; downstream operations include harvest, clarification, purification and formulation.

Constraint

Mass transfer, mixing, heat removal, sterility, process control and scale-up are central engineering tasks.

Metric

The process is judged as a chain: a highly productive reactor is not useful if recovery is impractical.

TERMS system boundary • mechanism • constraint• performance metric

Teaching focus: connect “Bioprocess engineering” to a measurable engineering decision. Ask which variable should be measured first, what assumption is most fragile, and how the conclusion would change at a different scale.

Metabolic engineering

- Metabolic engineering redirects cellular flux toward a target product by modifying pathways, regulation and cofactor balance.
- Strategies include pathway introduction, knockout of competing reactions, enzyme balancing, transporter engineering and dynamic control.
- Flux analysis links stoichiometric network structure to observable rates and yields.
- Successful designs balance product formation with the host's need for energy, precursors and redox homeostasis.

TERMS system boundary • mechanism • constraint• performance metric

Teaching focus: connect "Metabolic engineering" to a measurable engineering decision. Ask which variable should be measured first, what assumption is most fragile, and how the conclusion would change at a different scale.

Synthetic biology

- Synthetic biology emphasizes modular design, standardized methods and iterative Design–Build–Test–Learn cycles.
- Genetic circuits can implement sensing, logic, memory and control functions inside cells.



The field increasingly integrates automation, cell-free prototyping, genome engineering and machine learning.

A major challenge is context dependence: parts that work in one host or condition may behave differently elsewhere.

TERMS system boundary • mechanism • constraint• performance metric

Teaching focus: connect “Synthetic biology” to a measurable engineering decision. Ask which variable should be measured first, what assumption is most fragile, and how the conclusion would change at a different scale.

Protein and enzyme engineering

- Engineering can change catalytic activity, substrate specificity, stability, solubility or regulation.
- Rational design uses structural/mechanistic knowledge; directed evolution explores sequence space experimentally.
- Modern approaches combine high-throughput screening with computational prediction and machine learning.
- Industrial success depends on both molecular performance and compatibility with production and purification processes.

TERMS system boundary • mechanism • constraint• performance metric

Teaching focus: connect “Protein and enzyme engineering” to a measurable engineering decision. Ask which variable should be measured first, what assumption is most fragile, and how the conclusion would change at a different scale.

Biomedical engineering

ENGINEERING LENS

Define → Measure → Model → Compare → Improve

- Biomedical engineering applies quantitative design to diagnosis, treatment, monitoring and replacement of biological function.
- Examples include medical devices, implants, imaging systems, biosensors, drug delivery and computational physiology.
- Design must account for biocompatibility, reliability, usability, clinical workflow and patient variability.
- Translation requires evidence across preclinical, clinical, manufacturing and regulatory stages.

TERMS system boundary • mechanism • constraint • performance metric

Teaching focus: connect “Biomedical engineering” to a measurable engineering decision. Ask which variable should be measured first, what assumption is most fragile, and how the conclusion would change at a different scale.

Tissue engineering and regenerative medicine

- Tissue engineering combines cells, biomaterials and biochemical/physical cues to restore or model tissue function.
- Scaffolds provide architecture and mechanics while controlling cell adhesion, transport and degradation.
- Organoids and organ-on-chip systems create controlled models of human physiology and disease.
- A central engineering challenge is vascularization and mass transport in larger or more metabolically active constructs.

TERMS system boundary • mechanism • constraint• performance metric

Teaching focus: connect “Tissue engineering and regenerative medicine” to a measurable engineering decision. Ask which variable should be measured first, what assumption is most fragile, and how the conclusion would change at a different scale.

Drug delivery

- Drug-delivery systems control where, when and how fast a therapeutic agent is released.
- Design variables include particle size, material chemistry, surface properties, loading efficiency and degradation rate.



Targeting must overcome biological barriers such as clearance, membranes, mucus and tissue heterogeneity.

Performance must be evaluated in realistic biological contexts because simple in vitro assays can overpredict delivery efficiency.

TERMS system boundary • mechanism • constraint• performance metric

Teaching focus: connect “Drug delivery” to a measurable engineering decision. Ask which variable should be measured first, what assumption is most fragile, and how the conclusion would change at a different scale.

Biosensors and diagnostics

- A biosensor integrates biological recognition with transduction and signal interpretation.
- Recognition elements include enzymes, antibodies, nucleic acids, receptors or engineered cells.
- Key metrics include sensitivity, specificity, dynamic range, response time, stability and matrix tolerance.
- Real-world performance also depends on sample handling, calibration, user workflow and decision thresholds.

TERMS recognition • transduction • threshold • matrix effect

Teaching focus: connect “Biosensors and diagnostics” to a measurable engineering decision. Ask which variable should be measured first, what assumption is most fragile, and how the conclusion would change at a different scale.

Agricultural biological engineering

- Applications include engineered crops, microbial inoculants, biocontrol, precision diagnostics and bio-based inputs.
- Engineering goals may be yield, nutrient-use efficiency, drought tolerance, disease resistance or reduced chemical inputs.
- Field environments are variable and open, so ecological interactions and robustness are critical.
- Regulatory and public-acceptance considerations are often as important as laboratory performance.

TERMS system boundary • mechanism • constraint• performance metric

Teaching focus: connect “Agricultural biological engineering” to a measurable engineering decision. Ask which variable should be measured first, what assumption is most fragile, and how the conclusion would change at a different scale.

Environmental engineering biology

ENGINEERING LENS

Define → Measure → Model → Compare → Improve

- Engineered or selected organisms can degrade pollutants, recover resources, treat wastewater and transform waste streams.
- Bioremediation effectiveness depends on contaminant bioavailability, electron donors/acceptors, community interactions and environmental conditions.
- Environmental release introduces containment and monitoring challenges not present in closed industrial reactors.
- System-level evaluation should include ecosystem effects and long-term stability.

TERMS system boundary • mechanism • constraint• performance metric

Teaching focus: connect “Environmental engineering biology” to a measurable engineering decision. Ask which variable should be measured first, what assumption is most fragile, and how the conclusion would change at a different scale.

Circular bioeconomy

- Biological engineering can convert agricultural residues, municipal waste, CO_2-derived feedstocks and side streams into higher-value products.
- Circular design aims to keep carbon and nutrients in productive use while reducing waste and fossil resource dependence.



Economic feasibility depends on feedstock logistics, preprocessing, conversion yield and downstream purification.

Life-cycle assessment is needed to confirm environmental benefit.

TERMS system boundary • mechanism • constraint• performance metric

Teaching focus: connect “Circular bioeconomy” to a measurable engineering decision. Ask which variable should be measured first, what assumption is most fragile, and how the conclusion would change at a different scale.

Living materials

- Engineered living materials combine cells with a material matrix so that the material can sense, respond, self-repair or synthesize products.
- Examples include microbial cellulose, mineralizing bacteria and biohybrid scaffolds.
- Design must balance cellular viability with mechanical performance, containment and long-term function.
- This emerging area illustrates convergence between synthetic biology, materials science and manufacturing.

TERMS

mechanics • transport • degradation • interface

Teaching focus: connect “Living materials” to a measurable engineering decision. Ask which variable should be measured first, what assumption is most fragile, and how the conclusion would change at a different scale.

Biological carbon management

System

Engineering biology can contribute to carbon capture, utilization and storage through photosynthesis, microbial conversion, biomineralization and durable bio-based materials.

Mechanism

The relevant metric is not only fixation rate but net system-level carbon benefit.

Constraint

Energy inputs, land use, nutrient demand and product lifetime can dominate life-cycle performance.

Metric

Climate applications therefore require coupling biological design with process and systems analysis.

TERMS system boundary • mechanism • constraint• performance metric

Teaching focus: connect “Biological carbon management” to a measurable engineering decision. Ask which variable should be measured first, what assumption is most fragile, and how the conclusion would change at a different scale.

Case study: recombinant vaccine platform

- A vaccine platform links antigen design, expression host, upstream cultivation, purification, formulation and delivery.
- Speed and scalability are important during outbreaks, but quality and safety cannot be compromised.
- Platform technologies reduce development time by reusing validated process elements.
- Engineering value comes from standardizing what can be standardized while preserving product-specific controls.

TERMS system boundary • mechanism • constraint• performance metric

Teaching focus: connect “Case study: recombinant vaccine platform” to a measurable engineering decision. Ask which variable should be measured first, what assumption is most fragile, and how the conclusion would change at a different scale.

Case study: wastewater treatment

ENGINEERING LENS

Define → Measure → Model → Compare → Improve

- Microbial communities convert organic carbon and nitrogen compounds through coupled redox processes.
- Process engineers control residence time, oxygen transfer, sludge retention and nutrient ratios to shape community function.
- The “product” is treated water meeting discharge criteria rather than a purified molecule.
- Robustness to variable influent is more important than maximizing one pathway in isolation.

TERMS system boundary • mechanism • constraint • performance metric

Teaching focus: connect “Case study: wastewater treatment” to a measurable engineering decision. Ask which variable should be measured first, what assumption is most fragile, and how the conclusion would change at a different scale.

Case study: CAR-T cells

- CAR-T therapy treats engineered living cells as a personalized therapeutic product.
- Engineering spans receptor design, cell activation, gene transfer, expansion, quality control, logistics and patient treatment.
- Critical attributes include identity, viability, potency, persistence and safety.
- The manufacturing process is tightly linked to clinical function, illustrating the complexity of living medicines.

TERMS

chassis • burden • phenotype • context

Teaching focus: connect “Case study: CAR-T cells” to a measurable engineering decision. Ask which variable should be measured first, what assumption is most fragile, and how the conclusion would change at a different scale.

Comparing domains

- Biomanufacturing operates mainly in controlled closed systems and optimizes productivity and quality.
- Biomedical systems operate in patients and prioritize safety, efficacy, reliability and biocompatibility.
- Environmental applications operate in heterogeneous open systems and prioritize ecosystem compatibility, robustness and monitoring.
- Agricultural systems combine open-environment complexity with strong economic and societal constraints.

TERMS data quality • prediction • validation • domain shift

Teaching focus: connect “Comparing domains” to a measurable engineering decision. Ask which variable should be measured first, what assumption is most fragile, and how the conclusion would change at a different scale.

Shared engineering methods

- All domains require measurable specifications, model-based reasoning, characterization, iteration and risk management.
- Mass transport and kinetics matter in reactors, tissues, devices and environmental systems.
- Data quality, uncertainty and variability affect every domain.
- The common engineering language allows methods to transfer, provided context-specific constraints are respected.

TERMS system boundary • mechanism • constraint• performance metric

Teaching focus: connect “Shared engineering methods” to a measurable engineering decision. Ask which variable should be measured first, what assumption is most fragile, and how the conclusion would change at a different scale.

Translation: from proof of concept to impact

- Translation requires more than demonstrating a biological effect in a small experiment.
- Manufacturing, quality systems, regulation, cost, supply chain, user needs and safety must be considered early.



Technology readiness increases as uncertainty is reduced through progressively more realistic testing.

Early system-level thinking reduces late-stage redesign.

TERMS system boundary • mechanism • constraint• performance metric

Teaching focus: connect “Translation: from proof of concept to impact” to a measurable engineering decision. Ask which variable should be measured first, what assumption is most fragile, and how the conclusion would change at a different scale.

Regulatory context as a design input

ENGINEERING LENS

Define → Measure → Model → Compare → Improve

- Products may be regulated as drugs, devices, biologics, diagnostics, food, agricultural products or environmental releases.
- Regulatory classification determines evidence requirements, manufacturing controls and post-market obligations.
- Design choices such as material composition, host organism and delivery route can change the regulatory pathway.
- Regulation should therefore be treated as a design constraint, not only a final administrative step.

TERMS

system boundary • mechanism • constraint• performance metric

Teaching focus: connect “Regulatory context as a design input” to a measurable engineering decision. Ask which variable should be measured first, what assumption is most fragile, and how the conclusion would change at a different scale.

Risk–benefit trade-offs

- No technology is risk-free; responsible engineering compares expected benefit with the probability and severity of harm.
- Risk controls may include containment, redundancy, monitoring, fail-safe mechanisms and restricted operating conditions.
- The acceptable balance depends on application context and stakeholder values.
- Transparent documentation of uncertainty improves decision quality.

TERMS

hazard • exposure • containment • monitoring

Teaching focus: connect “Risk–benefit trade-offs” to a measurable engineering decision. Ask which variable should be measured first, what assumption is most fragile, and how the conclusion would change at a different scale.

Where the field is converging

- Automation and AI connect design to rapid experimental iteration.
- Synthetic biology and biomaterials are merging into programmable living systems.
- Advanced bioreactors, organ-on-chip platforms and real-time analytics are improving control at multiple scales.
- Sustainability and responsible innovation are increasingly integrated into engineering specifications rather than treated as afterthoughts.

TERMS system boundary • mechanism • constraint• performance metric

Teaching focus: connect “Where the field is converging” to a measurable engineering decision. Ask which variable should be measured first, what assumption is most fragile, and how the conclusion would change at a different scale.

Take-home map

- Biological engineering directions differ in application context but share a systems-engineering foundation.
- The most successful solutions integrate biology with transport, process design, data, control and manufacturing.



Performance metrics must be chosen for the domain: what counts as success in a fermenter differs from success in a patient or ecosystem.

Engineering decisions should connect local component performance to whole-system outcomes.

TERMS system boundary • mechanism • constraint• performance metric

Teaching focus: connect “Take-home map” to a measurable engineering decision. Ask which variable should be measured first, what assumption is most fragile, and how the conclusion would change at a different scale.

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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