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

Lecture 4

LOGIC AND METHODOLOGY OF SCIENTIFIC RESEARCH

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Aim of the Lecture

To introduce students to the logical foundations and methodological principles of scientific research, explain the role of scientific reasoning in developing and testing hypotheses, and demonstrate how research methodology ensures the validity and reliability of scientific results.

Key Concepts Covered

Scientific Logic

Principles of logical and critical thinking in research.

Methodology

Main approaches and methods of scientific research.

Hypothesis Testing

Formulation and verification of hypotheses.

Data Interpretation

Analysis, evaluation, and drawing valid conclusions.

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

1. Explain the fundamental principles of scientific logic and methodology.
2. Distinguish between inductive and deductive reasoning.
3. Describe the role of analysis, synthesis, abstraction, and generalization in scientific research.
4. Apply logical approaches to formulate research questions and hypotheses.
5. Evaluate the validity, reliability, and consistency of scientific conclusions.

AGENDA & PRESENTATION PLAN

LogicalReasoning:Induction, Deduction, Abduction

Foundations of Logic: Pillars of scientific knowledge

Methodological Frameworks: Epistemology and research design

Conceptual Structures: Theories, hypotheses & laws

Empirical Testing & Ethics: Validation, paradigms and integrity



THE CORE PILLARS OF SCIENTIFIC KNOWLEDGE

LOGIC: Formal rules governing valid reasoning. Ensures that conclusions follow necessarily from premises, providing the rational backbone of scientific argumentation and inference.

INTEGRATION: Logic and methodology work in tandem. Logical rigor validates reasoning steps while methodological discipline ensures empirical grounding and systematic inquiry.

METHODOLOGY: Principles and practices guiding research design, conduct, and evaluation. Provides structured procedures to generate reliable, replicable, and credible scientific findings.

RELIABLE KNOWLEDGE: Together, logic and methodology transform raw observations into verified, systematic scientific knowledge that can be tested, refined, and built upon over time.



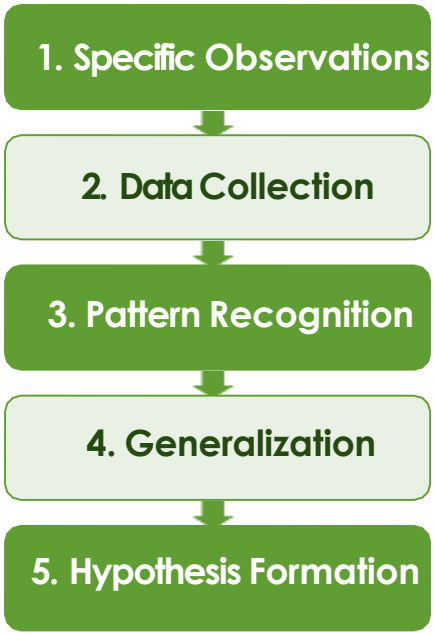
EPISTEMOLOGICAL FOUNDATIONS OF SCIENTIFIC RESEARCH

Concept /	Explanation / application
EPISTEMOLOGY	The branch of philosophy studying the nature, scope, and justification of knowledge — foundational to understanding how science produces valid claims.
R AT IONALISM	Relies on reason and deduction as primary sources of knowledge. Logical inference from established principles guides scientific theorizing.
EMPIRICISM	Grounds knowledge in sensory experience and measurable evidence. Observations and experiments are the ultimate test of scientific claims.
SCIENTIFIC KNOWLEDGE.	Emerges at the intersection of rationalism and empiricism — combining logical rigor with empirical validation to produce reliable, testable understanding.

THE SYSTEMIC NATURE OF SCIENTIFIC KNOWLEDGE

Concept /method	Explanation / application
CONCEPTS & H YPOT HE SE S	Scientific concepts group phenomena and link directly to hypotheses, forming the building blocks of coherent knowledge networks.
HYPOTHESES & THEORIES	Hypotheses integrate into broader theories, organizing facts into structured frameworks that explain and predict natural phenomena.
LOGICAL CONSISTENCY	Logical consistency ensures new findings fit existing frameworks or prompt systematic revision of established knowledge.

INDUCTIVE LOGIC IN SCIENTIFIC DISCOVERY



Recording individual empirical events and phenomena

Gathering systematic, repeatable measurements

Identifying recurring trends across data points

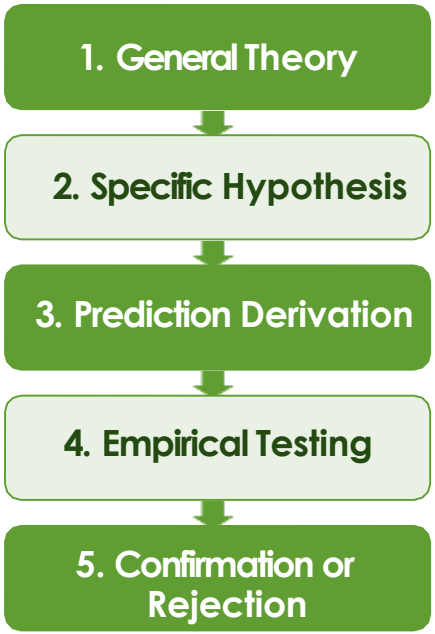
Extending observed patterns to broader contexts

Formulating a testable, falsifiable proposition

LIMITATIONS OF PURE INDUCTION

Concept /method	Explanation / application
PROBABILISTIC CONCLUSIONS	Inductive conclusions are never certain — they are probabilistic and can always be overturned by new evidence.
HUME'S PROBLEM OF INDUCTION	David Hume showed that one counter-example can disprove a universal generalization (e.g., one black swan).
TENTATIVE UNTIL TESTED	Scientific conclusions drawn from induction remain tentative and must be subjected to further empirical testing.

DEDUCTIVE LOGIC IN SCIENTIFIC TESTING



Broad premises accepted as foundational knowledge

Derived logically from the general theory

Testable predictions deduced from the hypothesis

Observations and experiments evaluate predictions

Results support or refute the original hypothesis

ABDUCTIVE REASONING

Concept / method	Explanation / application
BEST EXPLANATION	Abduction hypothesizes the most plausible explanation for incomplete or unexpected obser vations
KEY APPLICATIONS	Widely used in diagnostics, evolutionary studies, and scientific troubleshooting
GUIDING FURTHER TESTING	Does not guarantee truth, but directs researchers toward the most testable hypothesis

COMPARING INDUCTION, DEDUCTION & ABDUCTION

Concept /method	Explanation / application
INDUCTION	Bottom-up reasoning from specific observations to general conclusions. Conclusions are probabilistic and remain tentative.
DEDUCTION	Top-down reasoning from general principles to specific predictions. Conclusions are logically necessary if premises hold.
ABDUCTION	Diagnostic reasoning toward the most plausible explanation for surprising data. Guides further hypothesis testing.

SCIENTIFIC CONCEPTS & CATEGORIZATION

Concept / method	Explanation / application
ABSTRACT CONCEPTS	Concepts group phenomena sharing common properties, abstracting reality into communicable units of knowledge.
OPERATIONALIZATION	Translates abstract concepts into concrete, observable, and testable definitions for research use.
MEASURABLE VARIABLES	Enables clarity and empirical testability by quantifying conceptual properties in research.

SCIENTIFIC HYPOTHESES

Concept /method	Explanation / application
VARIABLE RELATIONSHIPS	Hypotheses predict relationships between independent and dependent variables, forming testable propositions.
LOGICAL CONSISTENCY	A valid hypothesis must be internally consistent and logically coherent with existing theoretical frameworks.
FALSIFIABILITY	Hypotheses bridge theory and empirical testing — they must be falsifiable to qualify as scientific claims.

THE NATURE OF SCIENTIFIC LAWS









INVARIANT RELATIONSHIPS: Lawsexpress consistent,repeatable relationships observed across all instances. They holduniversally under defined conditions and are not subject to exceptions within their domain of applicability.

DESCRIPTIVE NATURE: Laws describe what happens in nature — they capture regularities without explaining the underlying mechanisms or causes. They answer "how" phenomena behave, not "why" they occur.

MATHEMATICAL EXPRESSION: Scientific laws are often stated in precise mathematical form (e.g., $F = ma$, $E = mc^2$). This formalism enables exact prediction and quantitative testing across diverse experimental contexts.

DISTINCTION FROM THEORIES: Unlike theories, which explain mechanisms and integrate broader evidence, laws state observed regularities. Theories provide the causal framework that gives laws their explanatory depth and context.

SCIENTIFIC THEORIES

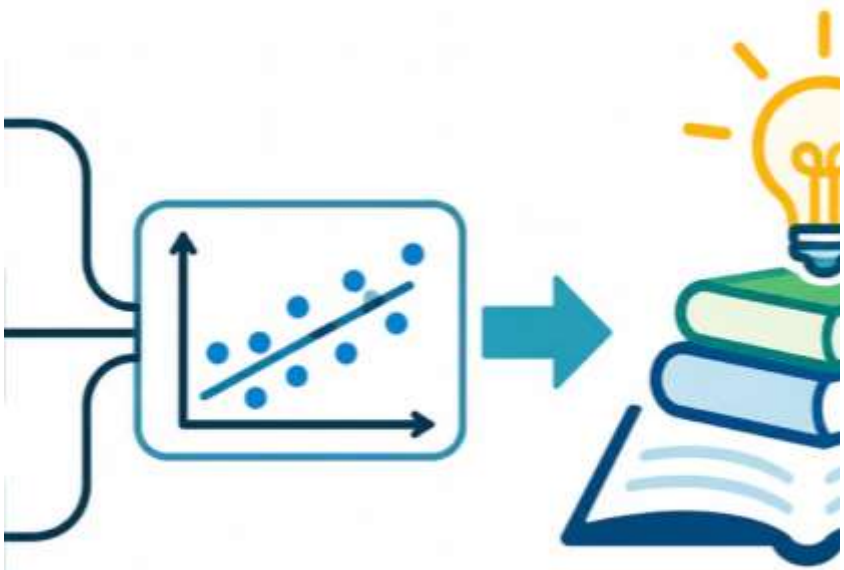
1.Empirical Foundation: Empirical facts form the basis of all theoretical knowledge.

2. Integration of Scientific Laws: Scientific laws are incorporated into theories to explain natural phenomena.

3. Synthesis of Hypotheses: Theories integrate multiple hypotheses into coherent explanatory frameworks.

4. Predictive Frameworks: Scientific theories generate broad, testable predictions about natural phenomena.

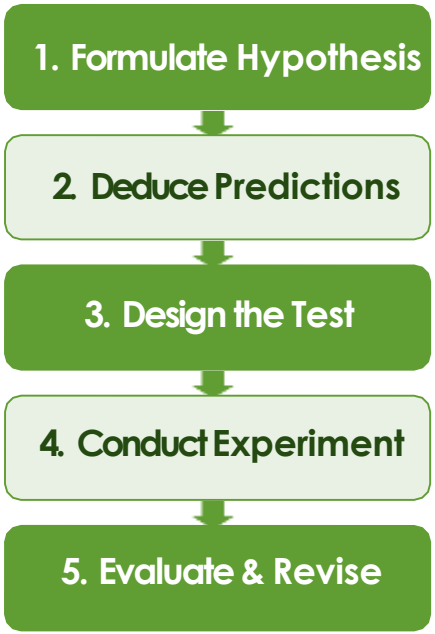
5. Robustness Through Testing: Theories are strengthened through repeated testing, empirical validation, and continuous refinement.



METHODOLOGICAL PRINCIPLES: OBJECTIVITY & NEUTRALITY

Concept / method	Explanation / application
OBJECTIVITY IN R E SEARCH	Objectivity requires independence from researcher bias and personal preferences, ensuring findings reflect reality rather than assumptions.
DOUBLE-BLIND DESIGNS	Neither participants nor researchers know group assignments, eliminating expectation bias and ensuring impartial data collection and evaluation.
RANDOMIZATION PROTOCOLS	Random assignment of subjects to experimental and control groups neutralizes confounding variables and strengthens internal validity of results.
STANDARDIZED PROCEDURES	Uniform protocols, automated data logging, and calibrated instruments reduce human error and ensure replicable, credible scientific outcomes.

THE HYPOTHETICO-DEDUCTIVE METHOD



Propose a testable, falsifiable prediction

Derive specific outcomes expected if hypothesis holds

Plan controlled experiment with variables defined

Collect empirical data under controlled conditions

Confirm, refute, or refine the hypothesis

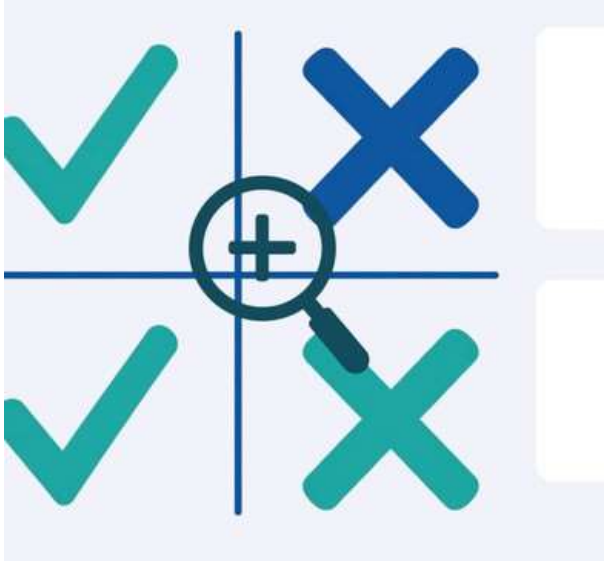
FALSIFIABILITY & POPPER'S CRITERION

POPPER'S PRINCIPLE:Karl Popper arguedthat aclaim isscientificonlyif it can, in principle, be proven false by empirical evidence. Unfalsifiable claims fall outside the domain of science.

FALSIFIABLE CLAIMS: Statements that can be tested and potentially refuted by observation or experiment. Example: "All metals expand when heated" — one counterexample disproves it.

UNFALSIFIABLE CLAIMS: Statements that cannot be disproven by any possible empirical test. Example: "Everything happens for a reason" — no experiment can refute it, so it is non-scientific.

SCIENTIFIC DEMARCATION: Falsifiability is the boundary between science and non-science. Only hypotheses open to empirical refutation qualify as scientific and contribute to testable knowledge.



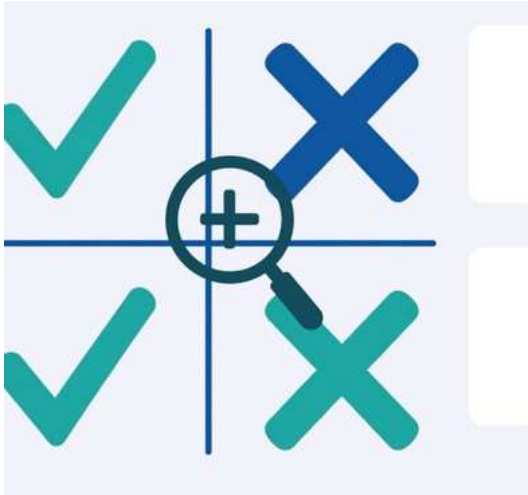
VERIFICATIONISM VS. FALSIFICATIONISM

VERIFICATIONISM: Seeksconfirmingevidence to validate hypotheses. Focuses on accumulating positive instances. Prone to confirmation bias and selective observation. Associated with logical positivism and early 20th-century philosophy of science.

FALSIFICATIONISM: Proposed by Karl Popper: actively attempts to disprove hypotheses. A claim is scientific only if it can be falsified. One counter-example is sufficient to reject a universal hypothesis. Stronger basis for scientific rigor.

COGNITIVE BIAS RISK: Verificationism is susceptible to confirmation bias — interpreting data to fit pre-existing beliefs. Falsificationism counters this by demanding critical testing and openness to disconfirming evidence.

MODERN METHODOLOGY: Contemporary scientific methodology favors falsificationism for greater rigor and objectivity. Peer review, replication, and pre-registration all reflect falsificationist principles in practice.



METHODOLOGY OF EXPERIMENTAL DESIGN

Concept / method	Explanation / application
Independent & Dependent Variables	Define what is manipulated (IV) and what is measured (DV) in the experiment
Controlling Confounding Factors	Isolate variables to ensure observed effects are due to the IV alone
Control Groups	Baseline comparison group that does not receive the experimental treatment
Random Assignment	Randomly allocate participants to groups to eliminate selection bias
Ensuring Replicability	Document protocols clearly so independent researchers can reproduce results

MEASUREMENT LOGIC & ERROR ANALYSIS

Concept / method	Explanation / application
MEASUREMENT & QUANTIFICATION	Measurements convert observable properties into numerical values using instruments, enabling objective comparison and mathematical analysis of phenomena.
SYSTEMATIC ERRORS	Consistent, reproducible biases caused by faulty calibration or flawed methodology. They skew results in one direction and must be identified and corrected.
RANDOM ERRORS	Unpredictable variability arising from uncontrolled factors. Unlike systematic errors, they scatter results around the true value and are reduced by repeated measurements.
ACCURACY & PRECISION GOALS	Accuracy reflects closeness to the true value; precision reflects consistency across trials. Rigorous science demands both for reliable, valid data collection.

STATISTICAL LOGIC AND INFERENCE

Concept / method	Explanation / application
NULL HYPOTHESIS SIGNIFICANCE TESTING	NHST evaluates whether observed data deviate significantly from what would be expected under the null hypothesis (H_0), guiding scientific conclusions.
P-VALUE INTERPRETATION	The p-value estimates the probability of observing results as extreme as the data, assuming H_0 is true. A low p-value (e.g., < 0.05) suggests evidence against H_0.
TYPE I ERROR (FALSE POSITIVE)	Rejecting a true null hypothesis. Controlled by the significance level (α). Reducing α lowers the risk of false positives but increases Type II error risk.
TYPE II ERROR (FALSE NEGATIVE)	Failing to reject a false null hypothesis. Controlled by statistical power ($1-\beta$). Balancing both error types is essential for valid inference.

MODELING AS A METHODOLOGICAL TOOL

Concept / method	Explanation / application
MODEL SIMPLIFICATION	Models abstract and simplify complex real-world systems to isolate key variables and dynamics, making phenomena tractable for analysis.
REAL-WORLD VALIDATION	Models must be validated against empirical data to ensure accuracy and avoid oversimplification that distorts scientific conclusions.
SIMULATION PROCESSES	Simulations run model scenarios iteratively, generating predictions and testing outcomes under varied conditions before empirical testing.
CROSS-DISCIPLINARY APPLICATIONS	Modeling is central to physical, biological, and computational sciences, enabling unified methodological frameworks across disciplines.

REDUCTIONISM AND HOLISM

REDUCTIONISM:Studies components inisolationtounderstand the whole.Breakscomplex systemsinto smaller,manageablepartsto analyze individual mechanisms and pathways in detail.

HOLISM: Studies integrated system properties that emerge from interactions. Focuses on the whole being greater than the sum of its parts, as in systems biology and ecology.

COMPONENT ISOLATION: Examines individual elements separately to identify specific functions and causal relationships. Common in molecular biology, genetics, and controlled laboratory experiments.

SYSTEM INTEGRATION: Examines how components interact and form emergent properties. Captures feedback loops, network effects, and dynamic behaviors invisible at the component level.



SCIENTIFIC PARADIGMS



Scientists workwithin a dominant paradigm, solving puzzles using accepted theories, methods, and assumptions without questioning foundational pr inciples.

Unexplained results and contradictions accumulate over time, challenging the existing paradigm and revealing its limitations.

Persistent anomalies trigger a state of crisis, prompting scientists to question core assumptions and explore alternative theoretical frameworks.

A revolutionary new paradigm replaces the old one, fundamentally transforming the scientific worldview and redefining research norms.

METHODOLOGICAL ERRORS & COGNITIVE BIASES

Concept / method	Explanation / application
Confirmation Bias	Favoring evidence that supports existing beliefs while ignoring contradictory data
Availability Heuristic	Overweighting easily recalled examples when estimating probability or frequency
Anchoring Bias	Over-relying on the first piece of information encountered during analysis
Data Distortion	Biases skew data collection, analysis, and interpretation of results
Mitigation Protocols	Blinding, pre-registration, peer review, and standardized procedures reduce bias

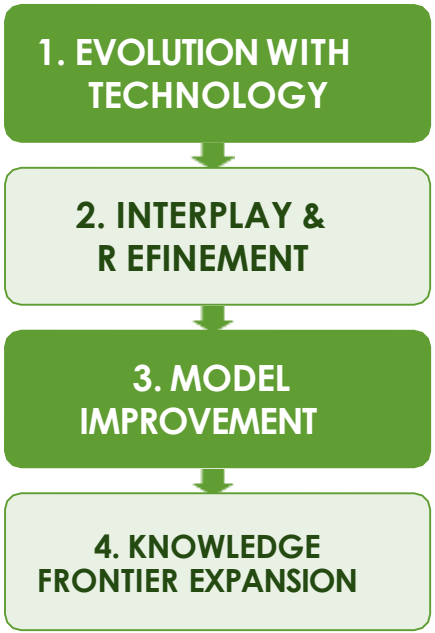
REPRODUCIBILITY AND THE SCIENTIFIC METHOD

Concept /method	Explanation / application
INDEPENDENT REPLICATION	Findings must be reproducible by independent researchers to confirm validity and eliminate chance or bias as explanations.
PROTOCOL TRANSPARENCY	Detailed, open documentation of methods and procedures allows others to replicate studies under identical conditions.
DATA SHARING	Making raw data publicly accessible enables verification, reanalysis, and meta-analysis by the broader scientific community.
NEGATIVE RESULTS R EPORT ING	Publishing null and negative findings prevents publication bias and strengthens the overall reliability of scientific knowledge.

ETHICAL METHODOLOGY AND RESEARCH INTEGRITY

Concept / method	Explanation / application
Honesty & Data Integrity	Accurate reporting of methods, results, and limitations without fabrication
Respect for Research Subjects	Protecting dignity, privacy, and informed consent of all participants
Misconduct Prevention	Avoiding fabrication, falsification, and plagiarism in all research
IRB Oversight	Institutional review ensures ethical compliance before and during research
Peer Accountability	Transparent peer review upholds standards and scientific credibility

SYNTHESIS: DYNAMIC UNITY OF LOGIC & METHOD



Logic and methodology continuously evolve alongside advances in technology, enabling new forms of inquiry and expanding the boundaries of scientific k nowledge.

The dynamic interplay between logical reasoning and methodological practice refines scientific models, corrects past errors, and sharpens the precision of inquiry.

Iterative cycles of hypothesis testing and theoretical revision improve scientific models, ensuring they better reflect empirical reality over time.

Science discovers new phenomena and expands knowledge frontiers through the unified application of rigorous logic and systematic methodology.

PRACTICAL ASSIGNMENT

Concept / method	Explanation / application
IDENTIFY REASONING	A researcher finds elevated microRNA in early- stage lung cancer patients and concludes causation. Identify the reasoning mode used and explain its key limitations.
FORMULATE H YPOT HE SE S	Formulate a falsifiable research hypothesis (H1) and a corresponding null hypothesis (H0) based on the microRNA and lung cancer scenario.
DESIGN THE EXPERIMENT	Outline an experimental design: define independent/dependent variables, control group, and controls to distinguish causality from correlation.

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