Example Student Learning Outcomes for Undergraduate Microbiology

ASM
Microbes Make Our World

2026

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Purpose of these Example Student Learning Outcomes

In 2024, the American Society for Microbiology published updated curriculum guidelines aligned to Vision and Change for Biology Education (Brewer and Smith, 2011). These guidelines were designed to be generalizable statements that describe foundational microbiology concepts (Boury *et al*., 2024) and they were then used to create an updated list of aligned, measurable example learning outcomes for benchmarking student understanding. Like the 2014 learning outcome guidelines, this updated list is designed to provide measurable, student-centric examples of what faculty COULD do in their courses and not intended to be comprehensive or prescriptive of what instructors MUST do in their classrooms.

What are learning outcomes?

Student learning outcomes are student-centered statements that specifically describe what learners are expected to know, understand, and do, at the conclusion of instructional activities in a course.

According to Robert Mager (Mager, 1997), learning outcomes are:

1) Specific and measurable, not broad and intangible. They rely on action verbs that precisely describe how achievement can be determined.

2) Focused on student performance and abilities. They describe what instructors intend students to learn, rather than listing what instructors will teach.

3) Descriptive of the intended student achievement (outcome), not the activities or processes instructors employ to help students achieve these outcomes.

The student focus and measurable nature of these statements distinguish them from listing content coverage (i.e., the ASM fundamental statements) that an instructor intends to “cover” (Wiggins and McTighe, 1998).

These updated example learning outcomes are aligned with both the updated ASM fundamental statements and the AAAS and National Science Foundation’s Vision and Change for Biology education. It is our hope that faculty use these examples as a starting point to organize their student focused microbiology courses and curriculum.

We built this document with the following principles:

- Each student learning outcome (SLO) is written to be measurable and student-centered. “At the end of this activity, students will be able to do a measurable thing.”

- Each fundamental statement has examples of learning outcome achievement that require lower order (memorization-based) and higher order (apply, create, evaluate) thinking (Bloom, 2010).

- Since the fundamental concepts in Vision and Change and in the ASM microbiology curriculum guidelines are interdependent, there are multiple learning outcomes that overlap between different core areas. For example, microbial growth curves and endospore development are each addressed by learning outcomes in “Structure and Function” as well as “Metabolic Pathways.”

References

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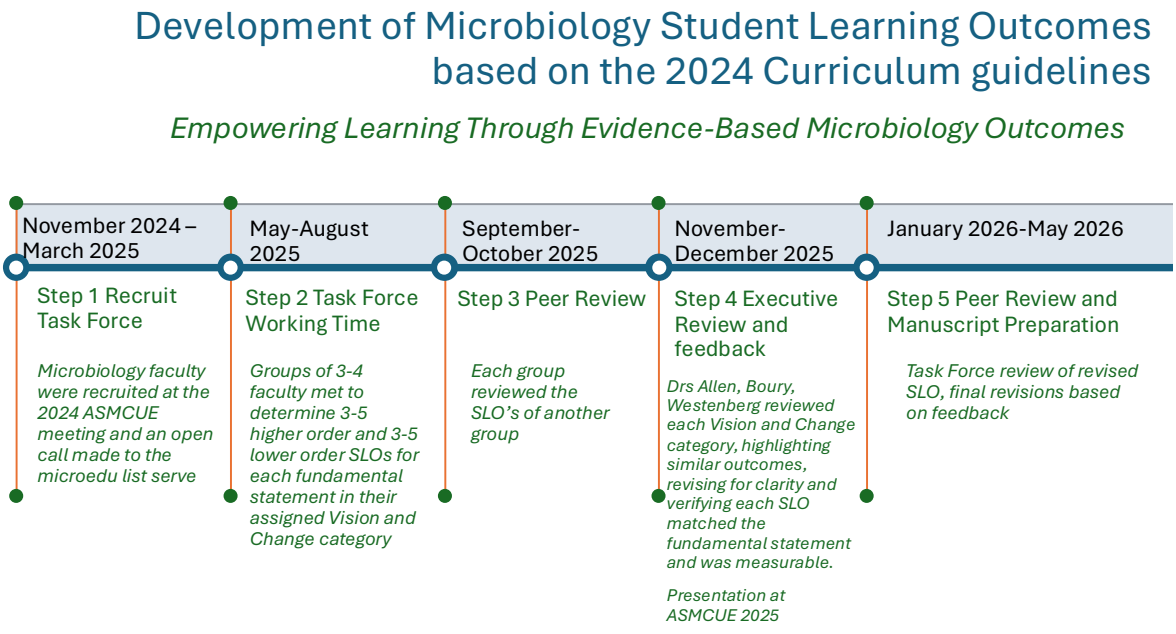
Task Force Process



PART I. FUNDAMENTAL STATEMENTS

EVOLUTION

1. All cells, eukaryotic organelles (e.g., mitochondria and chloroplasts), and major metabolic pathways evolved from early progenitor cells.

Examples of lower-order thinking learning outcomes include:

A. Identify properties shared by ALL microbial cells
B. Draw a basic timeline that indicates the relative timing of the first prokaryotic life, eukaryotic life, oxygenation of the environment, and multicellular life.
C. Draw a phylogenetic tree representing the evolutionary relationships between the three Domains. Label the LUCA and each Domain.
D. Diagram how endosymbiosis led to eukaryotic cells.

Examples of higher-order thinking learning outcomes include:

E. Compare and contrast the evolution of mitochondria and chloroplasts.
F. Summarize and critique the molecular, phylogenetic, and structural evidence supporting of the evolutionary origins of mitochondria and chloroplasts.

2. The diversity of microbes has arisen because processes that include horizontal gene transfer, mutation, reassortment, recombination, and natural selection in varying ecological niches favor the growth and survival of certain variants.

Examples of lower-order thinking learning outcomes include:

A. Differentiate between horizontal and vertical gene transmission and give an example of each.
B. Describe how characteristics unique to microorganisms contribute to their evolution and ecology.
C. Differentiate between mis-sense, non-sense, silent, and frameshift mutations.

Examples of higher-order thinking learning outcomes include:

D. Compare and contrast the processes of transformation, conjugation, and transduction.
E. Predict the effects of loss-of-function and gain-of-function mutations on bacterial phenotypes.
F. Predict the effects of increasing or decreasing communication, differentiation, motility and gene exchange within bacterial populations.
G. Design an experiment to distinguish between acquired and original genomic DNA.
H. Discuss the evolutionary advantages of quorum sensing and stress response-mediated transformation.
I. Compare and contrast DNA repair mechanisms between prokaryotes and eukaryotes
J. Correlate the rate of mutation with the activity of various DNA repair mechanisms.
K. Predict environmental conditions that would favor a “mutator” phenotype.

L. Explain the observation that RNA viruses typically have a higher mutation rate than DNA viruses.

3. The evolution of microbes is impacted by their interactions with the environment and a variety of ecological forces, including other microbes, humans, and habitats.

Examples of lower-order thinking learning outcomes include:

A. List three adaptations of microbes that allow them to live in specific environments.
B. List three different environmental factors that exert selective pressure on microbial populations.
C. Give three examples of microbes coevolving with their hosts.
D. Explain how antibiotic use leads to antibiotic-resistant populations of microbes.

Examples of higher-order thinking learning outcomes include:

E. Predict the adaptation of a microbe to a specific environment.
F. Analyze data demonstrating the emergence of populations of antibiotic-resistant microbes.
G. Evaluate the relative contributions of mutualism and competition on microbial community composition.
H. Compare and contrast bioaugmentation and biostimulation in terms of their suitability in bioremediation.
I. Explain why lab strains become attenuated over time and what strategies can be used to maintain virulence.
J. Create an antimicrobial treatment plan designed to reduce the risk of increasing antimicrobial resistance.
K. Propose an explanation for the origin of viruses and provide evidence that supports the hypothesis.

4. Phylogenetic trees best reflect the evolutionary relatedness of all organisms, although microbial lineages may be difficult to define due to horizontal gene transfer or lack of conserved genes.

Examples of lower-order thinking learning outcomes include:

A. Diagram and interpret the relationships in the universal tree of life based on small subunit rRNA data, showing the relationships among Archaea, Bacteria, and Eukarya.
B. Explain why the biological species concept is difficult to apply to defining microbial species.
C. Explain the polyphasic approach to microbial taxonomy.
D. Explain why ribosomal RNA genes are useful in determining phylogenetic relationships and list other genes that could also be used.
E. Explain how horizontal gene transfer confounds the interpretation of phylogenetic trees.

Examples of higher-order thinking learning outcomes include:

F. Compare and contrast phenotypic and genotypic methods for sorting microbial species.
G. Build a phylogenetic tree based on sequence data, describing the nodes and branches.
H. Use common bioinformatics software packages to align and compare genes, genomes, and metagenomes.

STRUCTURE AND FUNCTION

5. The structure and function of microbes are revealed by the use of microscopy, culture, and metabolic analyses, molecular methods, and bioinformatic tools.

Examples of lower-order thinking learning outcomes include:

A. Describe how different types of microscopes produce viewable images of microorganisms that can be used to differentiate cellular structures.
B. Explain how differential and selective culture media and metabolic tests are used to characterize bacterial species.
C. Explain the importance of specimen collection techniques for the correct identification of microbial species.
D. Outline the process of clinical diagnosis of infectious disease, from sample collection to identification.
E. Describe how DNA sequencing results are assembled or annotated to create defined microbial genomes.
F. Explain the process of PCR and how it is used to identify microbial species.

Examples of higher-order thinking learning outcomes include:

G. Categorize common lab tests as phenotypic, immunologic, or genotypic means of identifying microbes.
H. Compare and contrast staining processes, such as spore staining, Gram staining, and acid-fast staining.
I. Apply genetic diagnostic techniques to identify infectious agents.
J. Analyze data to draw conclusions about where to place organisms within a phylogenetic tree framework.
K. Plan a strategy for isolating and classifying a bacterial organism from an environmental or clinical sample using microscopy, differential and/or selective media, biochemical tests, and/or gene-based testing.
L. Design experiments to study microbial structures using microscopy, culture, molecular methods, and/or bioinformatic tools.

6. The distinct structures and processes in microbes can be targets for interspecies competition, antimicrobial treatments, and host immunity.

Examples of lower-order thinking learning outcomes include:

A. Describe the mechanism of action of antimicrobial drugs.
B. Describe adverse patient reactions to antimicrobial therapies.

C. Define selective toxicity in antimicrobial therapy.
D. Provide three reasons why it is easier to develop antibacterial drugs than it is to develop selectively toxic antiviral or antifungal drugs.
E. Describe how mechanisms leading to genetic diversity increase the frequency of antibacterial resistance alleles within a population.
F. Describe common targets of antivirals and explain why these selectively target viruses.
G. List five mechanisms of antimicrobial resistance.
H. Differentiate between probiotics and prebiotics.
I. Define cross-resistance and explain how it contributes to the development of multidrug-resistant strains.
J. Explain the processes that are used by host cells to identify and respond to virally infected cells.
K. Identify the components of the complement system and describe the three outcomes of complement activation.
L. List three examples of microbial-associated molecular patterns (MAMPS).
M. Describe methods used to control the growth of microorganisms in various environments.
N. Explain how a disease outbreak develops and what measures can be used to effectively control the spread of disease in a population.
O. Diagram the process of vaccination and explain how vaccines protect host organisms against infection.

<u>Examples of higher-order thinking learning outcomes include:</u>

P. Predict the effectiveness of an antibiotic against Gram-positive or Gram-negative bacterial cells, given the antibiotic's mechanism of action.
Q. Explain how the use of antibiotics affects microbiota.
R. Analyze the effectiveness of two different antimicrobials based on the target microbe and drug’s mechanism of action.
S. Evaluate the threat of increasing antibiotic resistance in bacterial populations based on different scenarios.
T. Given a description of an antiviral medication, predict whether it would be effective against RNA viruses, DNA viruses, or retroviruses.
U. Given a panel of biomolecules, predict which are most likely to be immunogenic (ex. polysaccharides, cytoplasmic proteins, outer membrane proteins, small RNAs).
V. Categorize the mechanism of action for antimicrobial compounds and predict their effect on bacterial cells. (i.e., -cidal vs -static)
W. Compare and contrast subunit, attenuated, killed, and mRNA vaccines in terms of their preparation and effects on host immunity.

7. Microbes have evolved structures adapted for specific functions that are often associated with a fitness advantage in a particular environment.

Examples of lower-order thinking learning outcomes include:

A. Discuss the biology of various virulence factors and how they enable a microbe to cause disease.
B. Explain how specialized structures (e.g., pili, capsules, endospores, LPS, flagella) enable a microbe to survive in a given environment.
C. Diagram the basic structure of a bacterial flagellum and explain how this structure is used to generate movement.
D. Explain how extreme temperatures, pH, or hypertonic conditions affect microbial growth and describe how extremophiles adapt to these conditions.
E. Explain how superantigens cause host pathology.
F. Outline the process that bacterial cells use to build biofilms and provide examples of how biofilms benefit bacteria.
G. Describe why siderophores are important for bacterial survival.
H. List characteristics of spore-forming bacteria that enable them to tolerate environmental extremes.

Examples of higher-order thinking learning outcomes include:

I. Compare and contrast endotoxins and exotoxins.
J. Predict how losing the ability to make a specialized structure (ex. pili/fimbriae, capsules, LPS, spores, or flagella) might affect microbial survival in a particular environment.
K. Design an experiment to identify virulence genes in a newly discovered microbial pathogen.
L. Evaluate how lysogenic conversion affects microbial fitness and virulence.
M. Compare and contrast the specific structures and processes that allow a pathogen and a hydrothermal vent microbe to survive in their respective environments.
N. Compare and contrast the structures of two (or more) organisms to predict which organism is best adapted for a given environment.
O. Compare and contrast the features of different environments, then generate hypotheses about the kinds of structures that would help an organism survive in each environment.
P. Design culture media and culture conditions needed to support the growth of specific types of microbes (e.g., thermophiles, psychrophiles, halophiles, mycoplasmas, anaerobes, aerobes, autotrophs).

8. Microbes have unique genomes, structures, and/or biochemical characteristics that distinguish them from each other.

Examples of lower-order thinking learning outcomes include:

A. Draw common cell morphologies found in Archaeal cells and Bacterial cells.

B. Draw a microbe from Domains Eukarya, Archaea, and Bacteria, labeling key structures in each.
C. Draw a Gram-negative bacterial cell, providing an explanatory label for pili, fimbriae, capsule, cell inclusions, nucleoid body, ribosomes, cell membranes, and porins.
D. Diagram the processes of DNA replication in Bacteria, Archaea, and Eukarya, labeling key structures and enzymes.
E. Differentiate between ribosomes in Bacteria, Archaea, and Eukarya.
F. Explain why endotoxins are unique to particular groups of microbes and how endotoxin structure can be used to differentiate microbial strains.
G. List characteristics of viruses that distinguish them from prokaryotic cells.
H. List targets of antiviral drugs and for each target explain why the drug against it is selectively targeted.
I. Identify specific biomolecules or cell structures that would be found in certain microbial cells (e.g., bacteria, fungi, algae) but would not be found in human cells.
J. Describe how endospores form and how they contribute to bacterial survival and spread of infectious diseases.
K. Describe common fungal morphologies and reproductive strategies.
L. Explain how pathogens are definitively connected to common-source outbreaks (like foodborne diseases).
M. Distinguish between different kinds of acellular infectious agents: viroids, satellite viruses, satellite RNAs, and prions.
N. Identify the type of host(s) for each infectious agent (viroids, satellite viruses, satellite RNAs, and prions) and the mode of transmission used by that agent.

<u>Examples of higher-order thinking Learning outcomes include:</u>

O. Compare and contrast the genomes of Bacteria, Archaea and Eukarya.
P. Compare and contrast Gram-positive and Gram-negative cells, describing two structures common to each and 2 structures unique to each cell type.
Q. Compare and contrast aerobic respiration, anaerobic respiration, and fermentation.
R. Compare and contrast processes of gene expression in Bacteria, Archaea and Eukarya, including enzymes and structures.
S. Predict which microbes would be most susceptible to different classes of antibiotics (e.g., membrane, cell wall, ribosome, and nucleic acid targeting drugs).
T. Compare and contrast viruses based on their genomes and physical structures.
U. Describe mechanisms of protein secretion that are shared among Bacteria, as well as mechanisms that are specific to Gram-negative Bacteria.
V. Design a workflow that would allow a lab to quickly distinguish between viral, bacterial, and fungal pathogens using genetic or biochemical characteristics.

9. The replication of viruses is determined by their unique structures, DNA or RNA genomes, and the cells they infect.

Examples of lower-order thinking Learning outcomes include:

A. Draw a naked and enveloped virus and label the structures found in each.
B. Diagram the stages of temperate and lytic viral replication cycles and identify the specific structures associated with each step.
C. Define RNA replicase, reverse transcriptase, integrase, and protease in the content of viral replication.
D. Give examples of viral enzymes that are enclosed within the capsid of the virion.
E. Diagram the processes of antigenic drift and antigenic shift.
F. Describe characteristics that make a virus host-specific.
G. List the seven types of viral genomes according to the Baltimore classification system.
H. Outline a process for isolating bacteriophage from the environment.

Examples of higher-order thinking Learning outcomes include:

I. Compare and contrast the host enzymes and viral enzymes needed by RNA viruses, DNA viruses, and retroviruses.
J. Compare and contrast lysogenic and latent viral infections.
K. Compare and contrast the structures and replication cycles of bacteriophages to animal viruses.
L. Explain why certain viral proteins must be in a virion instead of synthesized in the newly infected host cell.
M. Explain how antigenic drift and antigenic shift can both contribute to the emergence of new viruses.
N. Given a description of particular viral features (e.g. type of genome, presence of certain enzymes or genes, enveloped or non-enveloped, specificity of its spike proteins, etc.), predict and describe how it infects its host (e.g., types of tissues affected, latent vs. acute, mode of transmission, etc.)
O. Predict the type of genome a virus has based on the proteins packaged within its capsid.
P. Evaluate the viral needs from the host cell based on the viral genome.

10. Microbial reproductive cycles consist of sequential processes.

Examples of lower-order thinking Learning outcomes include:

A. Describe the steps of binary fission.
B. Explain the differences between microbial asexual and sexual reproductive cycles.
C. Name the phases of bacterial batch culture growth and describe what the cells are doing during each phase.
D. Calculate the number of cells present in a closed culture after a certain amount of time, given an organism’s doubling time.
E. Explain the concept of diauxic growth.

F. Describe how latency occurs with certain human viruses (herpes viruses, Epstein-Barr, varicella)
G. Diagram replication of DNA during binary fission.

Examples of higher-order thinking Learning outcomes include:

H. Compare and contrast binary fission with mitosis & meiosis.
I. Create hypotheses about the roles of early or late viral proteins during host infection.
J. Given a particular situation, present an argument for the best methods (ex. physical, chemical, biological) for controlling microbial growth.
K. Predict bacterial susceptibility to antibacterial drugs based on growth phase.

11. Obligate intracellular microbes require living host cells for replication.

Examples of lower-order thinking Learning outcomes include:

A. Explain how viruses are cultured and quantified in laboratory research.
B. Describe why obligate intracellular microbes cannot replicate in cell-free media.
C. Describe the viral one-step growth curve and explain important events that occur in each phase and how those events result in the final shape of the curve.
D. Arrange the steps of infection by bacteriophage in the correct order (for a temperate phage or a lytic phage).
E. Describe the replication process of retroviruses.
F. Explain how viruses are cultured and quantified in laboratory research.
G. Identify obligate intracellular microbes from a list. including both viral and bacterial examples.
H. Describe origins of endogenous viruses and their role in the function and evolution of the host
I. Describe the intracellular replication strategy of at least one obligate intracellular bacterium.

Examples of higher-order thinking Learning outcomes include:

J. Develop a strategy for inhibiting viral replication without interfering with the function of healthy host cells.
K. Analyze sample genomic data to identify why an obligate intracellular microbe cannot survive outside a host cell.
L. Evaluate data supporting the co-evolution of obligate intracellular bacteria and their hosts.
M. Predict how an obligate intracellular lifestyle influences genome size, metabolic capacity, and antibiotic susceptibility.
N. Compare and contrast vertical and horizontal microbial transmission with respect to maintenance of obligate intracellular microbes.
O. Analyze why some obligate intracellular bacteria are difficult to culture and how this impacts diagnosis and treatment.

METABOLIC PATHWAYS

12. Bacteria and Archaea exhibit extensive metabolic diversity, including nitrogen fixation, methane production, and anoxygenic photosynthesis, many of which are unique to these two domains.

Examples of lower-order thinking learning outcomes include:

A. Differentiate between the processes of substrate-level and oxidative phosphorylation.
B. Identify the substrates and products of fermentation.
C. Identify the substrates and products of methanogenesis.
D. Describe how methanogens generate cellular energy.
E. Describe the process of nitrogen fixation by nitrogen-fixing bacteria.
F. Differentiate between oxygenic and anoxygenic photosynthesis in terms of photosystems used, electron donors, and terminal electron acceptors.
G. Identify where glycolysis, the TCA cycle, the electron transport chain, and photosynthesis occur in Bacteria, Archaea, and Eukarya.
H. Describe three diagnostic tests used to determine specific metabolic characteristics of microbial isolates.
I. Calculate the change in standard reduction potential ($\Delta E^{\circ\prime}$) for redox reactions unique to Bacteria and Archaea using a redox tower.
J. Classify an organism as a chemoorganoheterotroph, chemolithoautotroph, chemolithoheterotroph, photolithoheterotroph, or photoorganoautotroph given its sources of energy, electrons, and carbon.

Examples of higher-order thinking learning outcomes include:

K. Illustrate the processes of oxidative and substrate-level and oxidative phosphorylation.
L. Debate which enzyme (nitrogenase, Ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCO) has a greater impact on terrestrial life.
M. Predict which environments are most likely to support methanogens.
N. Compare and contrast aerobic respiration, anaerobic respiration, and fermentation.
O. Compare and contrast the Embden-Meyerhof-Parnas, Entner-Doudoroff, and Pentose Phosphate pathways.
P. Describe how methanogenic microorganisms contribute to climate change and provide examples of environments where methanogens live.
Q. Explain why nitrogenase (the enzyme that reduces nitrogen gas to ammonia) has a unique cofactor called FeMoco.
R. Compare and contrast energy generation by methanogens to oxidative phosphorylation.

13. Intrinsic factors, such as genotype, metabolism, and cell structures, impact the survival and growth of microbes.

Examples of lower-order thinking learning outcomes include:

A. Draw a graph showing the four phases of bacterial population growth in batch culture and label each phase and describe what the cells are doing during each phase.

B. Identify on a graph the minimum, optimal and maximum growth rates at different temperatures.
C. Explain how catalase and super-oxide dismutase protect microbes that rely on oxygen for metabolism.
D. Describe endospores and explain how they impact the survival and growth of microbes.
E. Identify common protein and membrane adaptations found in psychrophiles and thermophiles and explain how they are adaptive for survival at extreme temperatures.
F. Describe how compatible solutes protect halophiles.
G. Differentiate between vegetative cells, endospores, fungal spores, and persister cells.
H. Given the starting concentration of a culture and the number of generations that occur, calculate the final concentration of bacteria in the culture.
I. Draw a diauxic growth curve labeling where lactose and glucose are used and indicate on the graph the concentrations of both sugars over time.
J. List cellular structures that impact survival and growth of microorganisms and for each explain the impact.

Examples of higher-order thinking learning outcomes include:

K. Compare and contrast the stringent, SOS, and heat shock responses in terms of triggers, actions, and resolution.
L. Correlate endospore structural properties to their ability to survive extremes of heat, chemicals, and radiation.
M. Predict how the standard reduction potential of different electron donors influences the concentration of these molecules required to support microbial growth.
N. Predict the glucose requirements of microbes growing using fermentation, anaerobic respiration, or aerobic respiration.
O. Analyze diauxic growth data to determine when bacteria switch from a preferred to a secondary carbon source and explain how cellular processes enable this shift.
P. Describe how fermentation can be used to transform fresh foods into foods that can be safely stored for later use.

14. Extrinsic factors, such as abiotic and biotic interactions in the environment, can impact survival and growth of microbes.

Examples of lower-order thinking learning outcomes include:

A. Define psychrophile, mesophile and thermophile.
B. Distinguish microbes that are halophiles from microbes that are halotolerant.
C. Identify if a microorganism is acidophilic or acidotolerant.
D. Define minimum, optimal and maximum growth temperatures.
E. Differentiate between disinfectants, antibiotics, and antiseptics in terms of use and mechanism of action.
F. Explain or diagram the molecular basis of how heat or high osmolarity inhibits or kills a microorganism.
G. Draw a graph showing the rate of growth across different temperatures for mesophilic, thermophilic, and psychrophilic bacteria, labeling the cardinal/optimum, maximum, and minimum temperatures.
H. Classify microorganisms into specific groups based on their oxygen, temperature, pH, and salt preferences (e.g. aerobes, anaerobes, thermophiles, acidophiles, halophiles).
I. Explain why antibiotic resistance genes are found in cells living in microbial communities that have never been exposed to modern antibiotics.
J. List methods of food preparation humans use to slow or stop microbial growth during food storage.

Examples of higher-order thinking learning outcomes include:

K. Predict where aerobes, obligate anaerobes, pure fermenters, facultative anaerobes, and microaerophiles will grow in test tubes of thioglycolate broth.
L. Predict which microbes would be most susceptible to different classes of antibiotics (e.g. membrane, cell wall, ribosome, and nucleic acid targeting drugs).
M. Predict how the shape of an exponential growth curve will change under different environmental conditions (temperature, nutrient availability, etc.)
N. Design a cleaning protocol for a variety of different situations (e.g. household kitchen vs hospital vs commercial food production) and describe relevant variables in each scenario.
O. Describe the challenges of achieving selective toxicity when designing drugs to treat protozoal, fungal, and viral infections.
P. Compare and contrast the impact of sterilization, disinfection, antisepsis, and sanitization on microbial communities.
Q. Given different foods (e.g strawberries vs milk vs meat) to preserve, describe an effective process to decrease the microbial load in each.
R. Describe how the non-specific immune response works to inhibit microbial growth (e.g. fever, engulfment, inflammatory response).
S. Describe how vaccination can provide protection from future disease.
T. Compare the relative sensitivity of a naked capsid and enveloped virus in harsh environmental conditions.
U. Compare how ionizing radiation and UV radiation kill cells.

15. Most microbial life is currently unculturable and therefore both cultivation-dependent and cultivation-independent techniques are used to identify microbial populations and their potential metabolic pathways.

Examples of lower-order thinking learning outcomes include:

A. Differentiate between selective and differential media and give examples of each.
B. Define genomics, metagenomics, transcriptomics, metatranscriptomics, proteomics, metaproteomics, and metabolomics.
C. List reasons the small subunit rRNA gene is used most often to determine phylogenetic relationships among organisms.
D. Provide two examples of cultivation-dependent and two examples of cultivation-independent techniques used to study microbial communities.
E. List possible reasons that most microbes remain unculturable.
F. Classify metabolic test media by the phenotypic characteristic(s) they detect.
G. Explain how a viral plaque assay works.

Examples of higher-order thinking learning outcomes include:

H. Compare and contrast complex and defined media in terms of use and ingredients in each medium.
I. Compare and contrast optical density, viable plate counts, direct counts, and dry weight in terms of their usefulness in determining microbial density in different contexts.
J. Design media and growth conditions needed to selectively culture nitrogen-fixing bacteria from soil samples.
K. Design an experiment to determine the metabolic characteristics of an unculturable microorganism.
L. Propose two hypotheses why many microorganisms are unculturable and design experiments to test each hypothesis.
M. Propose a scientific protocol for following the fate of a metabolite in a specific environment.
N. Describe the strengths and limitations of both cultivation-dependent and cultivation-independent methods for studying complex microbial communities.
O. Use common online bioinformatics tools (e.g. blast, Pfam, KEGG, kBase) to analyze metagenomic sequence data and infer the metabolic lifestyle of different microbes.
P. Predict the relative concentration of detectable microbes in a microbial community using culture-dependent and culture-independent approaches.
Q. Design a method for isolating a specific microbe from a given environment using either cultivation-dependent or cultivation-independent techniques.

INFORMATION FLOW AND GENETICS

16. Genetic variation can influence microbial structures and their functions.

Examples of lower-order thinking learning outcomes include:

A. Define transformation, conjugation, and transduction.

B. Define a mutation and describe ways mutations arise.
C. Define point mutation, genetic insertion, genetic deletion, and frameshift mutation.
D. Explain how horizontal gene transfer contributes to the spread of advantageous traits in a population.
E. Describe how horizontal gene transfer contributes to genetic variation in organisms that reproduce asexually.
F. Give an example of a way in which genetic variation enables a microorganism to survive and reproduce in a specific environment.

Examples of higher-order thinking learning outcomes include:

G. Illustrate the processes of transformation, conjugation, and transduction, indicating how each transfers DNA between bacterial cells.
H. Predict the effect of a specific mutation in the coding region of a bacterial gene on the resulting amino acid sequence, and/or shape, and/or function of the protein.
I. Predict the effect of a mutation in the gene(s) for a specific structure (e.g. flagella) on the function of the cell.
J. Compare and contrast the effects of a specific mutation in a regulatory region, such as a promoter or operator, to a mutation in an open reading frame.
K. Interpret the results of Griffith's classic experiment with rough and smooth genetic variants of *Streptococcus pneumoniae*.
L. Compare and contrast different mechanisms of horizontal gene transfer (HGT) and explain how they all contribute to the spread of specific traits in a population of bacteria.

17. Although the flow of information from DNA to RNA to protein is universal in all cells, aspects of the processes of replication, transcription, and translation differ between Bacteria, Archaea, and Eukarya.

Examples of lower-order thinking learning outcomes include:

A. Define promoter, coding sequence, start codon, stop codon, origin of replication, and ribosome binding site.
B. Describe differences in the structures of genes in Bacteria, Archaea, and Eukarya.
C. Draw a replication fork in Bacteria, Archaea, and Eukarya, labeling key enzymes and structures.
D. Draw a transcription bubble as it would appear in Bacteria, Archaea, and Eukarya, labeling all the structures.
E. Draw a ribosome in Bacteria, Archaea, and Eukarya, labeling all the structures involved in translation.
F. Illustrate the central dogma using a single gene, its resulting mRNA, and its resulting protein, labeling the parts specific to each molecule.

Examples of higher-order thinking learning outcomes include:

G. Compare and contrast the sizes and structures of genomes in Bacteria, Archaea, and Eukarya

H. Compare and contrast transcription and translation in Bacteria, Archaea, and Eukarya.
I. Map differences in transcription and translation onto the evolutionary paths that gave rise to Bacteria, Archaea, and Eukarya.
J. Describe the limitations that prevent a eukaryotic protein from being expressed in bacteria and devise a system to overcome those limitations and express the eukaryotic protein in bacteria.

18. The regulation of gene expression is influenced by external and internal molecular cues and signals.

Examples of lower-order thinking learning outcomes include:

A. Describe the role of sigma factors in bacterial gene expression.
B. Explain how genes can be regulated at the levels of transcription, translation or post-translation.
C. Describe simple models of gene regulation in bacteria.
D. Differentiate between mechanisms for regulation of gene expression in Bacteria, Archaea and Eukarya.
E. Define transcriptional inducers, activators, repressors, and co-repressors.
F. Diagram how bacteria use quorum sensing to coordinate gene expression.
G. Define an operon and explain how operons regulate gene expression.

Examples of higher-order thinking learning outcomes include:

H. Compare and contrast mechanisms for regulation of gene expression in Bacteria, Archaea and Eukarya.
I. Illustrate a bacterial two-component signal transduction system that mediates a response to an external signal by controlling gene expression.
J. Compare and contrast how inducible and repressible operons regulate gene expression.
K. Given a bacterial strain with one or more mutations in the *lactose* operon, predict its resulting phenotype.
L. Predict how disruption of quorum sensing will impact the coordination of gene expression
M. Explain how gene regulation makes possible survival in variable environments.

19. Non-cellular infectious agents, such as viruses, prions, viroids, and satellites are dependent on host cell processes in order to replicate.

Examples of lower-order thinking learning outcomes include:

A. Draw a viral particle, labelling the envelope, capsid, and genome.
B. List enzymes unique to viruses and identify the types of viruses that have each enzyme.
C. Distinguish between viruses, satellite viruses, viroids, and prions.
D. Label the replication cycle of a virus and indicate which processes depend upon host materials.
E. Explain how cell structure determines the susceptibility of a cell to viral attachment.

F. List Bacterial and Archaeal defenses against phage infection and reinfection.
G. Describe how satellite viruses, viroids, and prions impact the host.

Examples of higher-order thinking learning outcomes include:

H. Compare and contrast the viral enzymes needed to replicate the genomes of RNA, DNA or retroviruses.
I. Compare and contrast how different kinds of RNA viruses deviate from the classic central dogma of molecular biology.
J. Given the presence or absence of particular host cell features, predict whether viruses, viroids, prions, and/or satellites would be able to infect and replicate in the host cell.
K. Create an antiviral that would specifically target a DNA, RNA or retrovirus.
L. Predict where in a eukaryotic cell viral genome replication could occur for DNA, RNA or retroviruses.
M. Describe the challenges of achieving selective toxicity when designing drugs to treat viral infections.

MICROBIAL ECOLOGY

20. Microbes are ubiquitous, found in diverse and dynamic ecosystems, where they use available resources and often form complex communities.

Examples of lower-order thinking learning outcomes include:

A. Describe a complex community formed by microbes.
B. Differentiate between species richness and abundance.
C. Identify one transformation in a biogeochemical cycle that is mediated by microorganisms.
D. List specific places where biofilms can be found.
E. Describe methods to detect microbes in any environment.

Examples of high

F. Explain why enrichment cultures can be a useful method for isolating rare species from a habitat (for example, soil).
G. Compare and contrast the roles of aerobic and anaerobic metabolism in a biogeochemical cycle.
H. Describe how methanogenic microorganisms contribute to climate change and provide examples of environments where methanogens live.
I. Explain how sequencing-based approaches enable the identification of microbial community structures.
J. Analyze or interpret data to identify differences in microbial communities from different locations or following a perturbation.
K. Diagram the process of biofilm formation and predict the effect of loss-of-function mutations in quorum sensing and polysaccharide production.
L. Evaluate the advantages and disadvantages of being in a biofilm for microbes.

21. Microbes and the environment interact with and affect each other.

Examples of lower-order thinking learning outcomes include:

A. Describe an example of microbes interacting with and impacting the environment.
B. List the impacts a keystone species may have on a microbial community.
C. Identify potential microbe-environment interactions in a given scenario.
D. Explain how the Earth's atmosphere changed to -oxic and the consequences of this change to the planet's natural history.
E. Describe how a microbial community might respond to an altered environment.
F. Describe how environmental exposures influence early microbiome composition and acquisition for a given host.
G. Describe how the microbiome changes with the age of the host.
H.

Examples of higher-order thinking learning outcomes include:

I. Diagram the role of nitrogen-fixing bacteria in nitrogen cycling.
J. Explain why microbes behave differently in pure culture than when they grow as members of a community.
K. Describe what might happen if a keystone species was removed from a community of soil microorganisms.
L. Predict potential interactions between microorganisms and the environment after specific disruptive conditions.
M. Design a protocol to optimize the growth of a specific microbe, describing the resources and conditions necessary.

22. Most microbes interact with hosts in beneficial or neutral ways, with a minority having a detrimental impact on their host.

Examples of lower-order thinking learning outcomes include:

A. Define mutualism, commensalism, parasitism, competition and predation.
B. List an example of a beneficial interaction between microbes and their hosts.
C. State 5 ways that having a diverse microbiome is beneficial to humans, animals, and plants.
D. Describe a symbiotic relationship between a microbe and a eukaryote.

Examples of higher-order thinking learning outcomes include:

E. Compare and contrast animal and plant microbiota in terms of types, location, and host-microbe interaction.
F. Analyze a specific host microbe-interaction to identify impacts on the host.
G. Illustrate with a drawing or concept map how microbe can shift from interacting with a host in beneficial or neutral ways to having a detrimental effect on the same host
H. Compare and contrast the roles of microbes in plant health, animal nutrition, and adaptation to a specific ecological niche.

23. The health of the environment and all organisms (microbes, plants, humans, other animals) are closely linked and interdependent, as described by the One Health paradigm.

Examples of lower-order thinking learning outcomes include:

A. Define the One Health paradigm and explain how it is used.
B. Describe how interactions between microbes and plant roots in the rhizosphere can affect human health.
C. Diagram the interactions between host, pathogen, and environmental factors that lead to the development of disease
D. Explain how changes in environmental conditions can influence disease transmission across species.

Examples of higher-order thinking learning outcomes include:

E. Build an infographic to illustrate how the One Health paradigm explains the spread of antibiotic-resistant bacteria amongst non-human animals, humans, and natural environments.
F. Analyze case studies of outbreaks that demonstrate the interconnectedness of environmental, plant, animal, and human health.
G. Predict how altering host, pathogen, or environmental factors changes disease risk or progression.

IMPACT OF MICROBES

24. Microbes and their communities are essential for supporting all life as we know it.

Examples of lower-order thinking Learning outcomes include:

A. Explain how ancestral cyanobacteria altered the Earth's atmosphere and subsequent evolution of life on Earth.
B. Define key roles microbes play in nutrient cycling and ecosystem stability.
C. Explain the importance of decomposition of organic matter by microbes.
D. Describe different ecological symbioses between hosts, their microbes and their environment.
E. Describe the impact of the human microbiome on health.

Examples of higher-order thinking: Learning outcomes include:

F. Explain how the "Great Oxygenation Event" created opportunities for new kinds of existing life on Earth.
G. Compare and contrast the structure and function of plant, soil, animal, and human-associated microbiota.
H. Create a proposal to evaluate the effects of disrupting microbial communities on the microbial communities and associated hosts.
I. Predict the effect of broad-spectrum antibiotics on the mammalian gut's microbial community composition.
J. Design an experiment to assess how microbial communities change in response to biotic and abiotic stressors.

25. Microbes are used as models that provide fundamental knowledge about life processes.

Examples of lower-order thinking: Learning outcomes include:

A. List three common microbial model organisms and describe at least one biological question you could answer for each.
B. Explain how knowledge of the regulation of *E. coli's* lactose operon helps us to understand the expression of other genes.
C. Explain how the Griffith, Avery, and Hershey-Chase experiments relied on microbial processes to identify that DNA is the source of genetic information.
D. List the advantages of using microbial models to learn about physiology and evolution that could apply to other organisms.

Examples of higher-order thinking Learning outcomes include:

E. Compare and contrast the use of bacterial, archaeal, viral, and eukaryotic systems to study gene regulation.
F. Propose a research question that could be explored using a microbial model system.
G. Design an experiment using a microbial model to test a hypothesis about gene function.
H. Compare and contrast bacterial and eukaryotic systems to identify conserved mechanisms and evolutionary adaptations in life processes.
I. Evaluate the advantages and limitations of using microbial models to study complex biological processes in higher organisms.

26. Humans leverage microbes and their products to address problems and improve quality of life.

Examples of lower-order thinking Learning outcomes include:

A. List five different products made by different microbes.
B. Describe how microbes are used in industrial, agricultural, medical, food production and environmental settings.
C. Identify challenges associated with using microbial systems in large scale projects (e.g. food production or industry).
D. Explain how genome editing tools derived from microbes can be used to improve human health and well-being.
E. Describe how microbial biotechnology can be used to mitigate climate change.

Examples of higher-order thinking: Learning outcomes include:

F. Evaluate the risks and benefits of using genetically modified microbes in industrial, agricultural, medical, food production and environmental applications.
G. Design a solution to a current issue using microbial biotechnology.
H. Justify the use of microbial interventions over chemical alternatives in public health or agriculture.
I. Evaluate current scientific evidence supporting the use of microbiome-based therapies (prebiotics, probiotics, synbiotics, postbiotics).
J. Propose a policy recommendation regarding the regulation of synthetic biology applications in microbes.
K. Analyze how microbial products (e.g., antibiotics, enzymes, probiotics) have transformed human health, agriculture, and industry, and assess their long-term societal impacts.
L. Design a microbial-based strategy to address challenges associated with climate change.

27. The extent of microbial diversity is largely unknown, and exploration of this diversity is critical to understanding microbes and their role in the biosphere.

Examples of lower-order thinking Learning outcomes include:

A. Define, in ecological terms the concepts of microbial ubiquity, abundance, and diversity.
B. List four different reasons why many microbes are unculturable.
C. Explain why extremophilic microbes are an appropriate model for studying possible life on other planets.
D. Summarize current methods for identifying unculturable microbes.
E. Explain how climate change may have affected the diversity and abundance of microbial life.

Examples of higher-order thinking Learning outcomes include:

F. Analyze how metagenomics has reshaped our understanding of microbial diversity.
G. Predict how discovery of microbes in extreme environments can contribute to our understanding of microbial roles elsewhere in the biosphere.
H. Design a research study to investigate the microbiome of a previously unstudied ecosystem.
I. Evaluate a newly discovered microbial ecosystem on the basis of the environmental factors present that limit or promote microbial growth.
J. Propose an enrichment strategy for culturing microbes from a variety of extreme environments (e.g salt flats, hot springs, glaciers, or caves).

28. A minority of microbes are pathogens that can cause diseases and harm host organisms, society, and ecosystems.

Examples of lower-order thinking Learning outcomes include:

A. Identify five major microbial pathogens and the diseases they cause.
B. Describe how pathogenic microbes differ from commensal microbes.
C. Diagram the cycle of infection for pathogens in general.
D. Describe five different routes of disease transmission.
E. Describe five ways in which pathogenic microbes are able to damage their hosts
F. Describe the advantages and limitations of using Koch's postulates to study a newly characterized disease.
G. Explain how colonization by a pathobiont like *Helicobacter pylori* can be both beneficial and harmful to a human host.
H. Identify several natural environments in which human pathogens would not grow and/or survive.

Examples of higher-order thinking Learning outcomes include:

I. Compare and contrast the mechanisms of pathogenicity between bacterial, eukaryotic, and viral pathogens.
J. Design a diagnostic plan to identify select microbial pathogens based on clinical presentation and laboratory tests.
K. Analyze the social and ecological impacts of emerging infectious diseases.
L. Critically evaluate the role of environmental change in the spread of pathogens.
M. Develop a community-based intervention plan to limit the spread of a specific microbial pathogen.

N. Assess the impact of public health policies on microbial disease management.
O. Explain the disease cycle to a variety of audiences, including scientists, policy makers, and the general public.

29. The extent of microbial damage can be minimized by host-derived and external factors, including the microbiome, antibiotics, and immunity.

Examples of lower-order thinking Learning outcomes include:

A. Describe the first, second, and third line of defenses in the mammalian immune system.
B. Describe how the human microbiome can prevent colonization by pathogens.
C. Compare the mechanisms of action of different antimicrobial agents (e.g. anti-fungal, anti-bacterial, and anti-viral agents).
D. Diagram a bacterial cell, labeling structures commonly targeted by specific antibiotics.
E. Describe how vaccines enhance adaptive immune responses.
F. Explain how the adaptive immune response displays specificity, memory, and tolerance.
G. Describe how immunological principles are used in medicine, agriculture, biotechnology, food, and environmental science.

Examples of higher-order thinking Learning outcomes include:

H. Compare and contrast vertebrate, invertebrate, and plant immune responses that limit the spread of disease.
I. Compare and contrast innate and adaptive immune responses to microbial infections.
J. Analyze how immune system dysregulation contributes to disease processes such as autoimmune disorders, allergies, cancer, and chronic inflammation.
K. Assess the consequences of antimicrobial overuse on microbial resistance.
L. Develop a strategy to combat antimicrobial resistance using stewardship principles and novel therapies.
M. Propose a multifactorial approach to manage microbial threats using phage therapy, microbiome manipulation, immunology, and drug therapy.
N. Design a public health campaign to combat misinformation about the use of antibiotics or vaccines.
O. Compare and contrast four different vaccine types in terms of safety, stability, and effectiveness.
P. Design ideal antimicrobial agents for use in treating disease in plants, animals, and humans.
Q. Explain how genomic rearrangement, alternate splicing, and hypermutation in lymphocyte cells contribute to the generation of antibody diversity against pathogens.

PART II. SCIENTIFIC THINKING AND MICROBIOLOGY LABORATORY SKILLS

1. Apply scientific methods:

a. Investigate microbial systems.

Examples of lower-order thinking Learning outcomes include:

1. Identify major characteristics of microbial life.

2. Follow standard operating protocols (SOP) to perform aseptic technique, staining, and culturing procedures accurately.
3. Describe the steps involved in culturing and isolating microbes.
4. Classify microorganisms based on biochemical characteristics.
5. Define key components of the scientific method used in microbiology experiments.
6. Use a microscope to observe and record bacterial morphology

Examples of higher-order thinking Learning outcomes include:

7. Apply the scientific method to explain observed phenomena in a living system.
8. Interpret relatedness between different organisms using a phylogenetic tree.
9. Propose explanations for observed patterns of microbial growth based on data.
10. Design an investigation to explore microbial diversity in a given environment.

b. Formulate hypotheses and design well-controlled experiments.

Examples of lower-order thinking Learning outcomes include:

1. Differentiate between research questions, hypotheses and predictions.
2. Recognize independent and dependent variables in an experiment.
3. Explain the significance of positive and negative controls in determining the reliability of experimental results.

Examples of higher-order thinking Learning outcomes include:

4. Formulate a testable hypothesis based on background research and predict expected results
5. Design an experiment, proposing independent, dependent, and controlled variables likely to lead to credible results.
6. Determine whether observed experimental results match predictions and refute or support hypotheses.

c. Analyze, troubleshoot, and interpret results from a variety of methods. Draw evidence-based conclusions.

Examples of lower-order thinking Learning outcomes include:

1. Compare observations with what is known and identify discrepancies.
2. Describe the purpose of a method and explain what type of information it provides.
3. Summarize the basic principles behind commonly used techniques and appropriate controls.

Examples of higher-order thinking Learning outcomes include:

4. Document experimental data to facilitate the interpretation of results.
5. Evaluate data to draw evidence-based conclusions.
6. Interpret conflicting results and propose explanations.
7. Identify causes of anomalous results based on test and control group data.
8. Identify the role of statistics in analysis of experimental results.

d. Document and communicate the methods, results, and conclusions.

Examples of lower-order thinking Learning outcomes include:

1. Maintain a detailed record of laboratory experiments and results.
2. Make careful observations and record them in real-time.
3. Record experimental data accurately using correct microbiological terminology.
4. Distinguish between the results and discussion sections of a scientific report.
5. Write a methods section suitable for a primary paper.
6. Construct graphs and tables that effectively communicate experimental results.

Examples of higher-order thinking Learning outcomes include:

7. Organize and present data using tables and graphs to answer experimental questions.
8. Present experimental results in an oral, poster, or narrative format.
9. Summarize methods, results, and conclusions in a lab report.
10. Construct a scientific report that includes supported conclusions.

e. Collaborate, give and receive feedback, update methods and reassess conclusions.

Examples of lower-order thinking Learning outcomes include:

1. Explain minor changes to standard laboratory protocols (SOP) in lab reports or notebooks.
2. Collaborate with peers to develop hypotheses and predictions, design experiments, and analyze and interpret results.
3. Provide and respond to constructive feedback.

Examples of higher-order thinking Learning outcomes include:

4. Incorporate feedback to revise lab reports.
5. Design a revised experimental procedure based on an analysis of inconclusive results.
6. Critique peer protocols and recommend evidence-based improvements.
7. Assess peer lab reports using detailed rubrics.

f. Use quantitative reasoning and computational skills, such as mathematical reasoning, graphing, and statistics to evaluate and interpret data in microbiology.

Examples of lower-order thinking Learning outcomes include:

1. Graph bacterial growth curves.
2. Identify data for which the geometric mean is more appropriate than the arithmetic mean and calculate the geometric mean from a set of values.
3. Calculate CFU/mL or PFU/mL from dilution and plate/plaque count data.
4. Use a standardized data table to interpret experimental results.

Examples of higher-order thinking Learning outcomes include:

5. Calculate evolutionary distance using rRNA data.

6. Analyze data using appropriate statistical methods and software packages.
7. Identify uses for and limitations of generative artificial intelligence (AI) in microbiology.
8. Use common bioinformatics software packages to align and compare genes, genomes, transcriptomes, and metagenomes.

2. Properly prepare, view, and analyze specimens using microscopy.

Examples of lower-order thinking Learning outcomes include:

A. Identify parts of a microscope and their functions.
B. Perform basic sample preparation techniques.
C. Perform basic staining techniques and discuss the basis for each stain.
D. Generate a high-quality image using darkfield, phase contrast or brightfield microscopy.
E. Identify strategies to improve resolution
F. List the steps of the Gram stain, explain the function of each, and interpret results.
G. Determine the size of an object or organism using an appropriate scale.

Examples of higher-order thinking Learning outcomes include:

H. Predict if a stain will bind cellular material, the background, or neither, based on the overall charge of its chromophore.
I. Demonstrate proficiency using a microscope.
J. Compare microscopy techniques for different specimen types.
K. Determine whether brightfield or phase contrast microscopy will yield the best view of a given specimen.
L. Troubleshoot poor image quality or preparation artifacts.

3. Apply appropriate microbiological, molecular, serological, and bioinformatics methods to isolate and differentiate microorganisms.

Examples of lower-order thinking Learning outcomes include:

A. Explain how specific techniques work to isolate and differentiate microorganisms.
B. Perform fundamental techniques to isolate and differentiate microorganisms.
C. Use serological techniques to differentiate microorganisms.
D. Identify the appropriate techniques to identify and differentiate microorganisms from specific environments.
E. Use different types of bacterial culture media to grow, isolate, and identify microorganisms.
F. Explain how a PCR screen for specific genes is performed and how this technique is used to identify specific microorganisms.
G. Identify the positive and negative controls in a PCR screen for genetically-modified organisms and describe what can be learned from each control.

Examples of higher-order thinking Learning outcomes include:

H. Design a selective medium for a specific microbe from the nutritional requirements of that microbe.
I. Select appropriate methods to identify an unknown organism.
J. Isolate a specific type of microorganism from a complex community and characterize its colony and cellular characteristics, metabolic activities, antibiotic susceptibility, and/or genetic features.
K. Evaluate bioinformatics data to draw conclusions about the identity of specific microbes.

L. Distinguish between common fungi and parasites based on their cellular morphology.
M. Describe each component of an ELISA including antigen, primary and secondary antibodies, and chromagen, and interpret the results.

4. Estimate the number of microorganisms in a sample by direct or indirect means.

Examples of lower-order thinking Learning outcomes include:

A. Estimate the number of microorganisms in a sample using methods such as direct cell counts, viable plate counts, or spectrophotometric measurements.
B. Explain how to perform a viral plaque assay and how to interpret the results.
C. Demonstrate proper serial dilution technique and calculate CFU or PFU.
D. Correlate turbidity and CFUs with cell numbers in a broth culture.
E. Represent bacterial growth data on a semi-log scale.

Examples of higher-order thinking Learning outcomes include:

F. Choose the best quantification method for specific situations.
G. Compare and contrast the different methods of estimating numbers of microorganisms and identify the best method for a given application.
H. Critique the reliability of quantification results and suggest improvements.

5. Practice microbiology in a responsible and safe manner, using appropriate safety equipment and adhering to emergency procedures and guidelines.

Examples of lower-order thinking Learning outcomes include:

A. Demonstrate aseptic technique in lab procedures.
B. Differentiate between the required precautions for different Biosafety Levels (BSL).
C. List the Personal Protective Equipment necessary while performing a specific microbiology technique.
D. List proper locations for the disposal of specific items used in the laboratory.
E. Safely use physical mechanisms and chemical agents to control microbial populations.
F. Locate and identify available emergency equipment in the laboratory.

Examples of higher-order thinking Learning outcomes include:

G. Evaluate lab procedures for safety compliance.
H. Develop a new SOP that addresses emerging biosafety concerns.
I. Accurately follow laboratory safety rules, procedures, and universal precautions.

6. Effectively communicate fundamental concepts of microbiology with consideration of scientific and non-scientific audiences.

Examples of lower-order thinking Learning outcomes include:

A. Explain basic microbiological terms.
B. Explain scientific findings to a variety of audiences.
C. Present, write, and converse using microbiology-specific terminology.

Examples of higher-order thinking Learning outcomes include:

D. Create a communication product (e.g., infographic, video) for a general public audience.
E. Tailor explanations for different audiences based on their background knowledge.
F. Write a quantitative comparative statement with the 4"Cs": calculation, context, comparison, and clarity.
G. Interpret and report experimental procedures and results presented in formats such as laboratory notebooks, research reports, talks, and/or posters.
H. Communicate scientific findings intentionally addressing the audience, context, and purpose of the message.

7. Identify, interpret, and evaluate credible sources of information and cite them appropriately.

Examples of lower-order thinking Learning outcomes include:

A. Locate peer-reviewed articles using databases.
B. Cite sources using a format appropriate to the context.
C. Describe the steps involved in research paper publication, including the process of peer review.
D. Explain how a reader can establish if a source is credible.

Examples of higher-order thinking Learning outcomes include:

E. Critically evaluate the credibility of scientific sources.
F. Synthesize information from multiple sources to build an argument.
G. Evaluate the role of AI-assisted tools in searching for, summarizing, and citing scientific sources and use them appropriately in academic and professional contexts.
H. Apply proper citation practices when AI tools are used to assist in research, following institutional or disciplinary guidelines.
I. Reflect on ethical use of AI in academic research and communication.

8. Describe the intersection between science and society, such as emerging technologies, policy development, the importance of ethics in the scientific process, and recognize the historical and ongoing contributions of diverse scientists.

Examples of lower-order thinking Learning outcomes include:

A. Describe the rules in place to protect the rights of human subjects in scientific research.
B. Identify contributions of diverse scientists.

C. Identify the potential positive and negative social impacts of microbiological research and its applications.
D. Provide examples of situations in which society has influenced scientific endeavors.
E. Describe scientific discoveries that have influenced society.

Examples of higher-order thinking Learning outcomes include:

F. Analyze how microbiological discoveries influence public policy or practices.
G. Reflect on the impact of underrepresented voices in shaping science.
H. Evaluate how scientific knowledge can lead to societal change through an awareness of the limits and responsibilities of the scientific process.
I. Discern whether an AI tool is appropriate or inappropriate for a specific application.
J. Compare how different entities respond to technologies for the microbial sciences