FUNDAMENTAL PRINCIPLES and CONCEPTS for the BIOLOGIST

BIO 2010 - Transforming Undergraduate Education for Future Research Biologists*

Understanding the unity and diversity of life requires mastery of a set of fundamental concepts.

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Biological systems show remarkable unity at the molecular and cellular levels, reflecting their common ancestry. Variations on this unity lead to the extraordinary diversity of individual organisms. **Biology students should understand the unifying features of Life by acquiring the biological concepts listed below**. Biology faculty should consider the various points in their courses at which the concepts will fit. They should also consider the concept lists for chemistry, physics, and mathematics that follow and the ways in which those ideas could be incorporated into biology courses.

Notions of emergent behavior, pattern formation, and dynamical networks is central to understanding biology.

85 Significant Concepts of Biology Every Student Should Learn

Central Themes

1. All living things have evolved from a common ancestor, through processes that include natural selection and genetic drift acting on heritable genetic variation.
2. Biological systems obey the laws of chemistry and physics.
3. Structural complexity and information content are built up by combining simpler subunits into multiple complex combinations.
4. Understanding biological systems requires both reductionist and holistic thinking because novel properties emerge as simpler units assemble into more complex structures.
5. Living systems are far from equilibrium. They utilize energy, largely derived from photosynthesis, which is stored in high-energy bonds or ionic concentration gradients. The release of this energy is coupled to thermodynamically unfavorable reactions to drive biological processes.
6. Although fundamental molecular and cellular processes are conserved, biological systems and organisms are extraordinarily diverse. Unlike atoms and simple molecules studied in chemistry and physics, no two cells are identical.
7. Biological systems maintain homeostasis by the action of complex regulatory systems. These are often networks of interconnecting partially redundant systems to make them stable to internal or external changes.
8. Cells are fundamental units of living systems. Three fundamental cell types have evolved: bacteria, archea, and eukaryotes.
9. Living organisms have behavior, which can be altered by experience in many species.
10. Information encoded in DNA is organized into genes. These heritable units use RNA as informational intermediates to encode protein sequences, which become functional on folding into distinctive three-dimensional structures. In some situations RNA itself has catalytic activity.
11. Most biological processes are controlled by multiple proteins, which assemble into modular units to carry out and coordinate complex functions.
12. Lipids assemble with proteins to form membranes, which surround cells to separate them from their environment. Membranes also form distinct compartments within eukaryotic cells.
13. Communication networks within and between cells, and between organisms, enable multicellular organisms to coordinate development and function.

14. In multicellular organisms, cells divide and differentiate to form tissues, organs, and organ systems .with distinct functions. These differences arise primarily from changes in gene expression.
15. Many diseases arise from disruption of cellular communication and coordination by infection, mutation, chemical insult, or trauma.
16. Groups of organisms exist as species, which include interbreeding populations sharing a gene pool.
17. Populations of species interact with one another and the environment to form interdependent ecosystems with flow of energy and materials between multiple levels.
18. Humans, as well as many other species, are members of multiple ecosystems. They have the capacity to disrupt or preserve the ecosystems upon which they depend.

Additional Quantitative Principles and Concepts Useful to Biology Students

Rate of Change

19. This can be a specific (e.g., per capita) rate of change or a total rate of change of some system component.
20. Discrete rates of change arise in difference equations, which have associated with them an inherent time-scale.
21. Continuous rates of change arise as derivatives or partial derivatives, representing instantaneous (relative to the units in which time is scaled) rates.

Modeling

22. The process of abstracting certain aspects of reality to include in the simplifications of reality we call models.
23. Scale (spatial and temporal) - different questions arise on different scales.
24. What is included (system variables) depends on the questions addressed, as does the hierarchical level in which the problem is framed (e.g., molecular, cellular, organismal).
25. There are trade-offs in modeling-no one model can address all questions. These trade-offs are between generality, precision, and realism.
26. Evaluating models depends in part on the purpose for which the model was constructed. Models oriented toward prediction of specific phenomena may require formal statistical validation methods, while models that wish to elucidate general patterns of system response may require corroboration with the available observed pat- terns.

Equilibria and Stability.

27. Equilibria arise when a process (or several processes) rate of change is zero.
28. There can be more than one equilibrium. Multiple stable states (e.g., long-term patterns that are returned to following a perturbation of the system) are typical of biological systems. The system dynamics may drive the process to any of these depending on initial conditions and history (e.g., the order of any sequence of changes in the system may affect the outcomes);
29. Equilibria can be dynamic, so that a periodic pattern of system response may arise. This period pattern may be stable in that for some range of initial conditions, the system approaches this period pattern.
30. There are numerous notions of stability, including not just whether a system that is perturbed from an equilibrium returns to it, but also how the system returns (e.g., how rapidly it does so).
31. Modifying some system components can lead to destabilization of a previously stable equilibrium, possibly generating entirely new equilibria with differing stability characteristics. These bifurcations of equilibria arise in many nonlinear systems typical in biology.

Structure.

32. Grouping components of a system affects the kinds of questions addressed and the data required to parameterize the system.
33. Choosing different aggregated formulations (by sex, age, size, physi- ological state, activity state) can expand or limit the questions that can be addressed, and data availability can limit the ability to investigate effects of structure.
34. Geometry of the aggregation can affect the resulting formulation. . Symmetry can be useful in many biological contexts to reduce the complexity of the problem, and situations in which symmetry is lost (symmetry-breaking) can aid in understanding system response.

Interactions.

35. There are relatively few ways for system components to interact. Negative feedbacks arise through competitive and predator-prey type interactions, positive feedback through mutualistic or commensal ones.
36. Some general properties can be derived based upon these (e.g., two-species competitive interactions), but even relatively few interacting system components can lead to complex dynamics.
37. Though ultimately everything is hitched to everything else, signifi- cant effects are not automatically transferred through a connected system of interacting components-locality can matter.
38. Sequences of interactions can determine outcomes-program order matters.

Data and Measurement.

39. Only a few basic data types arise (numeric, ordinal, categorical), but these will often be interconnected and expanded (e.g., as vectors or arrays).
40. Consistency of the units with which one measures a system is important.
41. A variety of statistical methods exist to characterize single data sets and to make comparisons between data sets. Using such methods with discernment takes practice.

Stochasticity

42. In a stochastic process, individual outcomes cannot be predicted with -certainty. Rather, these outcomes are determined randomly according to a probability distribution that arises from the underlying mechanisms of the process. Probabilities for measurements that are continuous (height, weight, etc.), and those that are discrete (sex, cell type) arise in many biological contexts.
43. Risk can be identified and estimated. . There are ways to determine if an experimental result is significant. . There are instances when stochasticity is significant and averages are not sufficient.

Visualizing

44. There are diverse methods to display data.
45. Simple line and bar graphs are often not sufficient. . Nonlinear transformations can yield new insights.

Algorithms

46. These are rules that determine the types of interactions in a system, how decisions are made, and the time course of system response.
47. These can be thought of as a sequence of actions similar to a computer program, with all the associated options such as assignments, if-then loops, and while -loops.

Concepts of Chemistry – pertinent for Biology Students

Atoms

48. Periodic table, trends (size, electronic properties, isoelectronic systems)

49. Orbitals and electronic configurations. Nuclear chemistry.

Molecules

50. Lewis structures
51. Molecular properties (shape, dipole moments, bond energies)
52. Bonding models (valence bond theory, molecular orbital theory)
53. Molecular interactions (ion pair, hydrogen bond, van der Waals).
    Metal ions and metal complexes.
54. Resonance and electron delocalization
55. Computational methods and modeling

Water and Aqueous Solutions

56. Structure and polarity of liquid water
57. Ionic compounds in aqueous solutions . Acid-base equilibria, pH, pK, indicators .
58. Hydrophobicicity and hydrophilicity

Chemical Reactions

59. Stoichiometry
60. Hydrocarbons, heterocyclic compounds and functional groups
61. Reaction types (acid-base, redox, addition, elimination, substitution)
62. Reactive intermediates: carbocations, carbanions, enols, enolates, free radicals
63. Mechanisms of selected classes of chemical reactions

Energetics and Equilibria

64. Enthalpy, entropy, and free energy
65. Equilibrium constant
66. Temperature dependence of equilibria
67. Electrochemistry, electrochemical cells, Nernst equation

Reaction Kinetics

68. Reaction rate laws and kinetic order
69. Transition states
70. Temperature dependence of kinetics
71. Catalysis, enzyme-catalyzed reactions, and the Michaelis-Menten equation
72. Diffusion-limited reactions
73. Thermodynamic versus kinetic stability

Biomolecules

74. Building blocks: amino acids, nucleotides, carbohydrates, fatty acids
75. Biopolymers: proteins, nucleic acids, polysaccharides
76. Three-dimensional structure of biological macromolecules
77. Molecular assemblies: micelles, monolayers, biological membranes.
78. Solid-phase synthesis of oligonucleotides and peptides.
79. Properties and synthesis of polymers

Analyzing Molecules and Reactions

80. Mass spectrometry
81. Absorption and emission spectroscopy (UV; visible, infrared) . NMR spectroscopy
82. Diffraction (x-ray, neutron, electron)
83. Electron microscopy and scanning probe microscopy
84. Separation methods: chromatography, electrophoresis, and centrifugation
85. Isotopic tracers and radioactivity

Concepts of Physics – pertinent for Biology Students

Principles of physics that are central to the understanding of biological processes. Life science majors should master these key physics concepts.

Motion, Dynamics, and Force Laws

86. Measurement: physical quantities, units, time/length/mass, precision
87. Equations of motion: position, velocity, acceleration, motion under gravity
88. Newton's laws: force, mass, acceleration, springs arid related material: stiffness, damping, exponential decay, harmonic motion
89. Gravitational and spring potential energy, kinetic energy, power, heat from dissipation, work
90. Electrostatic forces, charge, conductors/insulators, Coulomb's law. Electric potential, current, units, Ohm's law
91. Capacitors, R and RC circuits
92. Magnetic forces and magnetic fields
93. Magnetic induction and induced currents

Conservation Laws

94. Conservation of energy and momentum
95. First and Second Laws of thermodynamics

Thermal Processes at the Molecular Level

96. Thermal motions: Brownian motion, thermal force (collisions), temperature, equilibrium
97. Ideal gas statistical concepts using Boltzmann's law, pressure
98. Diffusion limited dynamics, population dynamics

Waves, Light, Optics, and Imaging.

99. Oscillators and waves
100. Geometrical optics: rays, lenses, mirrors
101. Optical instruments: microscopes and microscopy
102. Physical optics: interference and diffraction
103. X-ray scattering and structure determination
104. Particle in a box; energy levels
105. Spectroscopy
106. Other microscopies: electron, scanning tunneling, atomic force

Collective Behaviors and Systems far from Equilibrium

107. Liquids, laminar flow, viscosity, turbulence
108. Phase transitions, pattern formation, and symmetry breaking
109. Dynamical networks: electrical, neural, chemical, genetic