1. Compare the difference between potential and kinetic energy.
2. Define the two laws of thermodynamics and explain how they relate to biological systems.
3. Explain how ATP functions as an energy shuttle.
4. Describe how enzymes speed up chemical reactions.
5. Describe how cellular respiration produces energy that can be stored in ATP.
6. Describe the three main stages of cellular respiration.
7. Discuss the importance of oxidative phosphorylation in producing ATP.
8. Compare ATP generation from substrate level phosphorylation and oxidative phosphorylation.
9. Compare cellular respiration and fermentation.

Energy Transformation in cells

- Cells are small units, a chemical factory, housing thousands of chemical reactions.
- Cells use these chemical reactions for
  - cell maintenance,
  - manufacture of cellular parts, and
  - cell replication.

Energy

Energy is the capacity to cause change or to perform work.

There are two kinds of energy:
- Kinetic energy is the energy of motion.
- Potential energy is energy that matter possesses as a result of its location or structure.

Types of Energy used by Cells

- Heat or thermal energy, is a type of kinetic energy associated with the random movement of atoms or molecules.
- Light is kinetic energy, and can be harnessed to power photosynthesis.
- Electrical energy used in the nervous system.
- Chemical energy is responsible for all the biochemical reactions in the cell like ATP.
Thermodynamics

- Thermodynamics, science of the relationship between heat, work, temperature, and energy. In broad terms, thermodynamics deals with the transfer of energy from one place to another and from one form to another. The key concept is that heat is a form of energy corresponding to a definite amount of mechanical work.

Encyclopedia Britannica

- Scientists use the word system for the matter under study and surroundings for the rest of the universe.

Biological Thermodynamics

- Quantitative study of the energy transductions that occur in and between living organisms, structures, and cells and of the nature and function of the chemical processes underlying these transductions.

- Biological thermodynamics may address the question of whether the benefit associated with any particular phenotypic trait is worth the energy investment it requires.

Energy Transformations

Two laws govern energy transformations in living organisms.

- The first law of thermodynamics, energy in the universe is constant, (statement of the conservation of energy)

- The second law of thermodynamics, energy conversions increase the disorder of the universe.

- Entropy is the measure of disorder, or randomness.

Energy Transformations in Cells

- Cells use oxygen in reactions that release energy from fuel molecules.

- In cellular respiration, the chemical energy stored in organic molecules is converted to a form that the cell can use to perform work.
Energy and Chemical reactions

- Chemical reactions either
  - release energy (exergonic reactions) or
  - require an input of energy and store energy (endergonic reactions).

Exergonic reactions

Exergonic reactions release energy.
- These reactions release the energy in covalent bonds of the reactants
- Burning wood releases the energy in glucose as heat and light
- Cellular respiration
  - involves many steps,
  - releases energy slowly, and
  - uses some of the released energy to produce ATP.

Exergonic Reaction

Reactants

Energy

Products

Amount of energy released

Endergonic Reactions

Endergonic reaction
- requires an input of energy and
- yields products rich in potential energy.

Endergonic reactions
- begin with reactant molecules that contain relatively little potential energy but
- end with products that contain more chemical energy.

Endergonic Reaction

Reactants

Energy

Products

Amount of energy required

Photosynthesis: endergonic reaction

Photosynthesis is a type of endergonic process.
- Energy-poor reactants, carbon dioxide, and water are used.
- Energy is absorbed from sunlight.
- Energy-rich sugar molecules are produced.
### Metabolism

- A living organism carries out thousands of endergonic and exergonic chemical reactions.
- **Metabolism**: The total of an organism’s chemical reactions.
- **Metabolism = Anabolism + Catabolism**
- A metabolic pathway is a series of chemical reactions that either
  - builds a complex molecule or
  - breaks down a complex molecule into simpler compounds.

### Energy Coupling

- Energy coupling uses the
  - energy released from exergonic reactions to drive
  - essential endergonic reactions,
  - usually using the energy stored in ATP molecules.

### The Energy Currency of the Cell

- ATP, adenosine triphosphate, powers nearly all forms of cellular work.
- ATP consists of
  - the nitrogenous base adenine,
  - the five-carbon sugar ribose, and
  - three phosphate groups.
ATP drives cellular work

- Hydrolysis of ATP releases energy by transferring its third phosphate from ATP to some other molecule in a process called phosphorylation.

- Most cellular work depends on ATP energizing molecules by phosphorylating them.

ATP drives cellular work

- There are three main types of cellular work:
  1. chemical,
  2. mechanical, and
  3. transport
- ATP drives all three of these types of work

How enzymes function
Bioenergetics

**Biological Catalysts**

- Although biological molecules possess much potential energy, it is not released spontaneously.
  - An energy barrier must be overcome before a chemical reaction can begin.
  - This energy is called the activation energy ($E_a$).

**The Energy of Activation**

- We can think of $E_a$ as the amount of energy needed for a reactant molecule to move “uphill” to a higher energy but an unstable state so that the “downhill” part of the reaction can begin.
- One way to speed up a reaction is to add heat, which agitates atoms so that bonds break more easily and reactions can proceed but could also kill a cell.

**Enzymes lower energy of activation**

Enzymes

- are usually proteins, although some RNA molecules can function as enzymes.
- function as biological catalysts by lowering the $E_a$ needed for a reaction to begin,
- increase the speed of a reaction without being consumed by the reaction.

**Reaction with enzyme**

**Metabolic reaction in a cell with and without enzyme**
Bioenergetics

**Enzymes have a specific shape**

- An enzyme
  - is very selective in the reaction it catalyzes and
  - has a shape that determines the enzyme’s specificity.
- The specific reactant that an enzyme acts on is called the enzyme’s substrate.
- A substrate fits into a region of the enzyme called the active site.
- Enzymes are specific because their active site fits only specific substrate molecules.

**Some common enzymes**

- catalase
- lactase

**Conditions for optimum enzyme activity**

Every enzyme has optimal conditions under which it is most effective.
- Temperature affects molecular motion.
  - An enzyme’s optimal temperature produces the highest rate of contact between the reactants and the enzyme’s active site.
  - Most human enzymes work best at 35-40°C.
  - But high temperature disrupts the structure
- The optimal pH for most enzymes is near neutrality.
Bioenergetics

Enzyme activity

Temperature
pH
Enzyme Concentration
Substrate Concentration

Four Variables

Effect of heat on enzyme activity

IF ACTIVE SITE CHANGES SHAPE:
SUBSTRATE NO LONGER FITS

Even if temperature lowered - enzyme cannot regain its correct shape

Temperature

5- 35°C Increase in Activity

40°C - denatures

<5°C - inactive

Environmental Conditions can Cause Changes in Shape (Denaturing)

Rate of Reaction

pH

Narrow pH optima

Disrupt Ionic bonds – Structure

Effect charged residues at active site

Cofactors and coenzymes

- Many enzymes require nonprotein helpers called cofactors, which
  - bind to the active site and
  - function in catalysis.
- Some cofactors are inorganic, such as zinc, iron, or copper.
- If a cofactor is an organic molecule, such as most vitamins, it is called a coenzyme.
**Bioenergetics**

**Enzyme inhibitors**

- A chemical that interferes with an enzyme’s activity is called an inhibitor.
- Competitive inhibitors
  - block substrates from entering the active site and
  - reduce an enzyme’s productivity.

**Enzyme inhibition**

- Noncompetitive inhibitors
  - bind to the enzyme somewhere other than the active site,
  - change the shape of the active site, and
  - prevent the substrate from binding.

**Enzyme inhibitors regulate cell metabolism**

- Enzyme inhibitors are important in regulating cell metabolism.
- In some reactions, the product may act as an inhibitor of one of the enzymes in the pathway that produced it. This is called feedback inhibition.

**Feedback Inhibition**

- Many beneficial drugs act as enzyme inhibitors, including
  - ibuprofen, inhibiting the production of prostaglandins,
  - some blood pressure medicines,
  - some antidepressants,
  - many antibiotics, and
  - protease inhibitors used to fight HIV.
- Enzyme inhibitors have also been developed as pesticides and deadly poisons for chemical warfare.

**Some drugs, pesticides and poisons are enzyme inhibitors**
The Marathoners and the Sprinters

Cellular respiration is the process by which cells produce energy aerobically.

The different types of muscle fibers use different processes for making ATP:

- Slow-twitch fibers undergo aerobic respiration (in the presence of $O_2$), respiration are reddish in color as it contains myoglobin.
- Fast-twitch fibers undergo anaerobic respiration (in the absence of $O_2$).

Breathing and Cellular Respiration

Breathing and cellular respiration are closely related:

- Breathing brings $O_2$ into the body from the environment.
- $O_2$ is distributed to cells in the bloodstream.
- In cellular respiration, mitochondria use $O_2$ to harvest energy and generate ATP.
- Breathing disposes of the $CO_2$ produced as a waste product of cellular respiration.

The human energy requirement

- The body needs a continual supply of energy to maintain basic functioning: to breathe, to keep heart pumping and maintain body temperature.
- The brain requires 120 gm of glucose/day!
- ATP supplies energy (kilocalories) for voluntary activities.
- An average adult human needs about 2,000 kcal of energy each day.

Cellular respiration and ATP molecules

- Cellular respiration is an exergonic process that transfers energy from the bonds in glucose to form ATP.
- Cellular respiration:
  - Can produce up to 32-34 ATP molecules from each glucose molecule.
  - Captures only about 34% of the energy originally stored in glucose.
- Other foods (organic molecules) can also be used as a source of energy.
Breaking down Glucose

\[ C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{ATP} + \text{Heat} \]

What is kcal?

- A kilocalorie (kcal) is
  - the quantity of heat required to raise the temperature of 1 kilogram (kg) of water by 1°C,
  - the same as a food Calorie, and
  - used to measure the nutritional values indicated on food labels.

How can energy be released from glucose?

- Energy can be released from glucose by simply burning it.
- The energy is dissipated as heat and light and is not available to living organisms.

How do cells tap energy from glucose?

- On the other hand, cellular respiration is the controlled breakdown of organic molecules.
- Energy is
  - gradually released in small amounts,
  - captured by a biological system, and
  - stored in ATP.

The redox reaction in cells

- Movement of electrons from one molecule to another is an oxidation-reduction reaction, or redox reaction. In a redox reaction,
  - the loss of electrons from one substance is called oxidation,
  - the addition of electrons to another substance is called reduction,
  - a molecule is oxidized when it loses one or more electrons, and
  - reduced when it gains one or more electrons.
The Process

- A cellular respiration equation is helpful to show the changes in hydrogen atom distribution.
- Glucose
  - loses its hydrogen atoms and
  - becomes oxidized to CO₂.
- Oxygen
  - gains hydrogen atoms and
  - becomes reduced to H₂O.

The Redox Reaction in Cells

Glucose

C₆H₁₂O₆

+ 6 O₂ → 6 CO₂ + 6 H₂O + ATP + Heat

The Redox Reaction in Cells

Glucose

C₆H₁₂O₆

+ 6 O₂ → 6 CO₂ + 6 H₂O + ATP + Heat

Mitochondria in Action

Mitochondria in Action

BioFix
Cellular Respiration

Where does Cellular Respiration Occur?

Where does Cellular Respiration Occur?

What are the three phases of Cellular Respiration?

What are the three phases of Cellular Respiration?

Sengupta
The role of Oxygen in Cellular Respiration

- Cellular respiration can produce up to 38 ATP molecules for each glucose molecule consumed.
- During cellular respiration, hydrogen and its bonding electrons change partners.
  - Hydrogen and its electrons go from glucose to oxygen, forming water.
  - This hydrogen transfer is why oxygen is so vital to cellular respiration.

Glucose and Oxygen

- **Glucose**
  - loses its hydrogen atoms and
  - becomes oxidized to CO₂.
- **Oxygen**
  - gains hydrogen atoms and
  - becomes reduced to H₂O.

Controlled breaking of the glucose molecule to release energy

The controlled breakdown of glucose

- There are other electron “carrier” molecules that function like NAD⁺.
  - They form an energy ‘staircase’ where the electrons pass from one to the next down the next level.
  - These electron carriers collectively are called the electron transport chain.
  - As electrons are transported down the chain, ATP is generated.

The molecules in the process

I. Enzymes are necessary to oxidize glucose and other foods.
II. NAD⁺
  - is an important enzyme in oxidizing glucose,
  - accepts electrons, and
  - becomes reduced to NADH.
Bioenergetics

NAD+

- NAD\(^+\) picks up one hydrogen atom and another single electron from carbohydrate, becoming NADH.
- It will retain this form until it drops off its energetic electrons (and a proton) in a later stage of the energy-harvesting process.

ATP and oxidative phosphorylation

NADH passes electrons to the electron transport chain.
- As electrons “move” from carrier to carrier and finally to O\(_2\), energy is released in small quantities.
- The energy released is used by the cell to make ATP.

The Electron Carrier NAD+

- NAD\(^+\) within a cell, along with two hydrogen atoms that are part of the food that is supplying energy for the body.
- NAD\(^+\) is reduced to NADH by accepting an electron from a hydrogen atom. It also picks up another hydrogen atom to become NADH.
- NADH carries the electrons to a later stage of respiration then drops them off, becoming oxidized to its original form, NAD\(^+\).

Glycolysis: substrate level phosphorylation

- Uses two ATP molecules per glucose to split the six-carbon glucose.
- Makes four additional ATP directly when enzymes transfer phosphate groups from fuel molecules to ADP.
- Glycolysis produces a net of two molecules of ATP per glucose molecule.
Glycolysis harvests chemical energy by oxidizing glucose to pyruvate

- ATP is formed in glycolysis by substrate-level phosphorylation during which:
  - an enzyme transfers a phosphate group from a substrate molecule to ADP and ATP is formed.
  - two NADH molecules are produced for each initial glucose molecule and ATP molecules are generated.
- The compounds that form between the initial reactant, glucose, and the final product, pyruvate, are called intermediates.

From Glycolysis to Citric Acid Cycle

Pyruvate is chemically processed to enter the citric acid cycle:
- A large, multienzyme complex catalyzes three reactions in the mitochondrial matrix:
  - A carbon atom is removed from pyruvate and released in CO₂.
  - The remaining two-carbon compound is oxidized, molecule of NAD⁺ is reduced to NADH.
  - Coenzyme A joins with the 2-carbon group to produce acetyl CoA.

The citric acid cycle

- The citric acid cycle is also called the Krebs cycle (after the German-British researcher Hans Krebs, who worked out much of this pathway in the 1930s),
- Citric acid cycle processes two molecules of acetyl CoA for each initial glucose.
- Thus, after two turns of the citric acid cycle, the overall yield per glucose molecule is:
  - 2 ATP,
  - 6 NADH and
  - 2 FADH₂.
**Phase 3: Oxidative phosphorylation**

- Occurs in the cristae of mitochondria
  - The molecules of the electron transport chain are built into the inner membranes of mitochondria.
  - Uses the energy released by electrons “falling” down the electron transport chain to pump H⁺ across a membrane.
  - Harnesses the energy of the H⁺ gradient through chemiosmosis, producing ATP.
    - These ions store potential energy.
    - Requires an adequate supply of oxygen.

**Making ATP in Bulk**

- Electrons from NADH and FADH₂ travel down the electron transport chain to O₂.
- Oxygen picks up H⁺ to form water.
- Energy released by these redox reactions is used to pump H⁺ from the mitochondrial matrix into the intermembrane space.
- In chemiosmosis, the H⁺ diffuses back across the inner membrane through ATP synthase complexes, driving the synthesis of ATP.
The Electron Transport Chain

Oxidative Phosphorylation

ATP synthase

Interrupting cellular respiration can have both harmful and beneficial effects

Poisons of the Cellular Respiration

Review: Each molecule of glucose yields many molecules of ATP

• The total yield is about 32 ATP molecules per glucose molecule.
• This is about 34% of the potential energy of a glucose molecule.
• In addition, water and CO₂ are produced.
The overview of cellular respiration

**Bioenergetics**

The overview of cellular respiration

**The Energy Harvest**

Each molecule of glucose yields many molecules of ATP

- Glycolysis and the citric acid cycle together yield four ATP per glucose molecule
- Oxidative phosphorylation, using electron transport and chemiosmosis, yields 34 ATP per glucose
- These numbers are maximum
- Some cells may lose a few ATP to NAD$^+$ or FAD shuttles

**FERMENTATION: ANAEROBIC HARVESTING OF ENERGY**

Fermentation enables cells to produce ATP without oxygen

- Fermentation is a way of harvesting chemical energy that does not require oxygen. Fermentation
  - takes advantage of glycolysis,
  - produces two ATP molecules per glucose, and
  - reduces NAD$^+$ to NADH.
- The trick of fermentation is to provide an anaerobic path for recycling NADH back to NAD$^+$.

Fermentation enables cells to produce ATP without oxygen

- Your muscle cells and certain bacteria can oxidize NADH through lactic acid fermentation, in which
  - NADH is oxidized to NAD$^+$ and
  - pyruvate is reduced to lactate.
Fermentation enables cells to make ATP without oxygen

- Lactate is carried by the blood to the liver, where it is converted back to pyruvate and oxidized in the mitochondria of liver cells.
- The dairy industry uses lactic acid fermentation by bacteria to make cheese and yogurt.
- Other types of microbial fermentation turn
  - soybeans into soy sauce and
  - cabbage into sauerkraut.

Alcohol Fermentation

- The baking and winemaking industries have used alcohol fermentation for thousands of years.
- In this process yeasts (single-celled fungi)
  - oxidize NADH back to NAD⁺ and
  - convert pyruvate to CO₂ and ethanol.
Cellular respiration generates energy for cellular work by a process called chemiosmosis, which uses a gradient of hydrogen ions (H⁺) to pull electrons down. This gradient is created by ATP synthase, which pumps H⁺ to create the gradient. Glucose and organic fuels are oxidized in the process, using electrons to produce ATP. ATP is used to produce some energy for cellular work. ATP synthase uses electrons to pump H⁺ through a membrane to create the gradient.