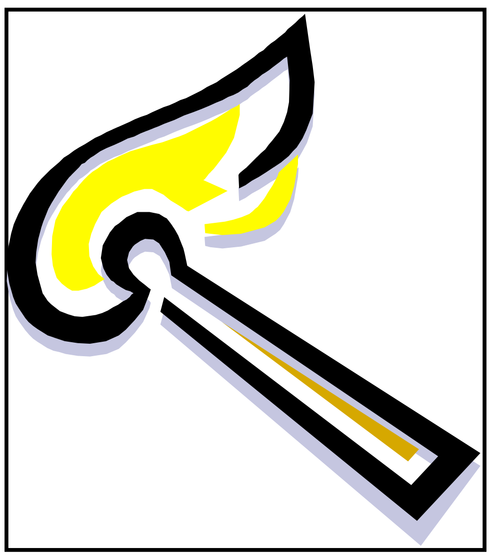
ENERGY AND THERMODYNAMICS (Biology)

A hands-on module designed to give biology, chemistry, and physics students concrete experiences related to the concepts of thermodynamics



Instructor Notes

to accompany the student materials, exercises, and experiments

MARICOPA COMMUNITY COLLEGES

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Opinions expressed are those of the authors and not necessarily those of the Foundation

ENERGY AND THERMODYNAMICS

An interdisciplinary science module
designed and developed by

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As part of the
Systemic Reform In Science (SyRIS) Project
of the Maricopa Community Colleges

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PREFACE

At most colleges and universities, the didactic teaching approach remains a fixture in introductory science classes despite numerous studies showing students retain little of the information taught. In addition, the approach neither fosters an interest in science nor promotes the critical thinking skills science demands. At the same time, students attending the Maricopa Community Colleges have become more ethnically and socioeconomically diverse. The result is that students enrolled in science courses today have a wider range of learning needs than students who took those courses in the past.

Therefore, a strong need exists to revise traditional science curriculum and pedagogy that is supported by national directions for science reform. These changes include a more concept-based/content-driven curriculum that incorporates collaborative learning, interactive lectures, inquiry-based methods, contextually-relevant exercises and examples, Internet research assignments, interdisciplinary content, problem-based learning, and other reformed teaching strategies. By having more science faculty better prepared for teaching students who, as a result of changes in university and workplace requirements and changing student demographics, have a wider range of learning needs, the quality of undergraduate science teaching will improve and enhance student interest and learning.

The SyRIS Project

Systemic Reform In Science (SyRIS) is a two-year, district-wide project designed to begin the process of improving student outcomes in science. The major goal of the project is the design, development, and field-testing of interdisciplinary science modules by science, math, engineering, and technology (SMET) faculty at the Maricopa Community Colleges. These modules incorporate current curriculum content in 100-level science courses and contain active learning strategies that will link science courses through real-life applications. We believe our efforts to reform instruction will translate into a better, more applied curriculum that will foster a keener interest in science and promote the thinking skills science and the business community require.

The 2000-2001 Interdisciplinary Science Modules are:

- **Catch the Waves**, Chandler-Gilbert CC – Pushpa Ramakrishna (Biology), Peer Mentor; Scott Adamson (Mathematics) and Tom Foster (Instructional Technology)
A module developed with concepts related to sound, water, and light waves. Students use the blackboard technology asynchronously to explore the interdisciplinary nature of waves.

- **Cells As Digital Images – An Investigation,** Estrella Mountain CC – Natalie Rivera (Mathematics), Peer Mentor; Rey Rivera (Mathematics) and Sandy Zetlan (Biology)
A module created for the collaboration between biology and mathematics students as they investigate a biological research question. Student research teams use biological, mathematical, and research methods to identify types of blood diseases. They make predictions and verify hypotheses using qualitative and quantitative approaches.

- **Energy and Thermodynamics,** Glendale CC – Karen Conzelman (Biology), Peer Mentor; Cheryl Dellai (Physics), Lisa Diebolt (Chemistry), and Bronwen Steele (Biology)
A hands-on module designed to enable physics, chemistry, and biology students to construct the fundamental concepts of thermodynamics from concrete experiences.
- **Don't Drink the Water**, GateWay CC – Reece Weide (Biology), Peer Mentor; Ernest Chavez (Mathematics), Jim Crimando (Biology), and Lisa Young (Water Technology)
Students explore water quality issues using problem-based learning. Elements of chemistry, biology, hydrology, math and communications skills are embedded within the course constructs, providing a real-world connection between concept and application.

- **The Problem with Pesticides,** Mesa CC – James Giles (Chemistry), Peer Mentor; A.J. Lombard (Geology), Cindy Odgers (Technology), and Terry Ponder (Biology)
A module designed to conduct activities dealing with pollution, chemicals in the environment, and pesticide use.

- **Global Warming,** Paradise Valley CC – David Harbster (Biology), Peer Mentor; Casey Durandet (Physics), Vanessa Montgomery (Biology), Stephen Nicoloff (Mathematics), and Shelle Witten (Library and Media Services)
A module that incorporates a personal energy and resource use audit to ascertain a student's general impact upon the environment. Working in teams, they analyze individual and group data to develop a broader perspective of the possible anthropogenic effects of climate change.

- **UV Radiation and Effects of Sunblocks,** Scottsdale CC – Suzanne Kelly (Biology), Peer Mentor); Patricia Ashby (Biology), Steve Borick (Chemistry), Paul Haugen (Physics), and Keith Worth (Mathematics)
This module presents central concepts of radiation: its origins, characteristics, and interaction with the earth's atmosphere and living organisms. It also includes information about the electromagnetic spectrum, the inverse square law, DNA mutations and cancer formation in living cells, the chemistry of ozone and chemical sunscreens, and modeling of data sets.

- **Water Pollution and Treatment**, South Mountain CC – Ann Scarbrough (Chemistry), Peer Mentor; Terry Fender (Mathematics and Physics) and Sian Proctor (Geology)
A module incorporating geological, physical, and chemical concepts in the evaluation of water purity and water treatment.

Acknowledgements
The SyRIS Project wishes to thank Dr. Anna Solley, Vice-Chancellor of Instruction and Student Affairs, Marybeth Mason, Director of the Maricopa Center for Learning and Instruction, and the Deans of Instruction at the Maricopa Community Colleges for their creative and financial support. In addition, partial support for this project was provided by the National Science Foundation through a Course, Curriculum, and Laboratory Improvement (Adaptation and Implementation) grant #DUE9952695.

Very special thanks are given to the Maricopa Community College SMET faculty members who have served as peer mentors and collaborative teams. It is their tireless efforts and creative energies that produced these interdisciplinary science modules.

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MODULE OVERVIEW

Background

Energy is a difficult topic for most non-science majors at least in part because it is not something tangible. Many non-science majors are still at Piaget's concrete level of reasoning, and consequently mathematical analyses, which help abstract thinkers to understand these concepts, are meaningless to these students. Biology students in particular seem to struggle in learning the important concepts related to thermodynamics (perhaps because there often are no math prerequisites for these courses). Yet these concepts are central to understanding metabolism and other biological phenomena.

In this module, we have developed and adapted relevant hands-on activities that give students concrete experiences with the central concepts of energy. These activities include ones that could be done in a classroom and others that are limited to a laboratory setting.

Intended Use

This module includes an alternative (more inquiry or constructivist-based) approach to a traditional lecture presentation of major concepts of thermodynamics included in the competencies of all biology courses; the laboratory component provides additional hands-on activities to further develop these core concepts and provide relevant real-life applications. This laboratory could supplement or replace existing laboratory experiments in this section of any of these courses.

Module Length

Three 50-minute lecture periods and one 170-minute lab.

Target Audience

Non-science majors courses in biology, but could be adapted for majors courses.

Methods/Strategies Used to Promote Active Learning

Understanding energy phenomena is central to all fields of science. A set of core concepts common to biology, fundamental chemistry, and physics courses have been used to develop this module. Learning strategies include:

- Constructivist-based instruction.
- Hands-on activities/demonstrations in both classroom and the laboratory
- Collaborative learning groups/classroom research ("in your seat" problems)
- "Real-life" applications to aid students in relating concepts to experiences outside of the classroom and to assess understanding

Module Objectives

Students will be able to:

- Describe and apply the first and second laws of thermodynamics to natural phenomena.
- Identify exergonic and endergonic reactions and draw energy diagrams to illustrate the change in free energy for each.
- Explain the importance of thermodynamically coupled reactions to organisms and give examples of such reactions.
- Describe energy transfers and transformations.
- Distinguish between kinetic and potential energy.
- Describe energy of activation and explain its relationship to reaction rates.

Module Structure

This energy and thermodynamics module will be done over three 50-min class periods and one 170-min laboratory period.

- **CLASSROOM EXPLORATION – PART 1 (total time: 50 minute period)**
  Objective: This unit uses hands-on activities and a PowerPoint presentation (PPT1) to explore and develop the concepts of energy (kinetic and potential) and the first law of thermodynamics.

- **CLASSROOM EXPLORATION – Part 2 (total time: 50 minute period)**
  Objective: This unit uses hands-on activities and a PowerPoint presentation (PPT2) to explore and develop the concepts of exergonic and endergonic reactions, and energetically coupled reactions.

- **CLASSROOM EXPLORATION – Part 3 (total time: 50 minute period)**
  Objective: This unit uses hands-on activities and a PowerPoint presentation (PPT3) to explore and develop the concepts of entropy and the second law of thermodynamics. It also develops the concept of activation energy and importance of enzymes to biological systems.

- **LABORATORY ACTIVITY – (total time: 170 min period)**
  Objective: Energy concepts are applied as students measure and compare the relative Caloric content of some common foods by measuring the change in temperature of water during their combustion. These laboratory determined values are compared to nutritional Caloric content using an on-line database. Generalizations are drawn about the efficiency of energy transfer in the two techniques, the relative Caloric content of the foods and its relationship to their respective compositions, and differences in total energy in foods versus nutritionally usable Calories.

- **HOMEWORK ASSIGNMENT**

Capstone activity that requires students to synthesize classroom explorations and laboratory experiences and to apply module concepts to new situations. Can be used as an instructional assessment tool.

Classroom Exploration – Part 1

Energy and the First Law of Thermodynamics: Answers

Instruction: Use PowerPoint presentation 1 (PPT1 – 18 slides) to explore and develop the concepts of energy (kinetic and potential) and the first law of thermodynamics. PPT1 notes are on page 4.

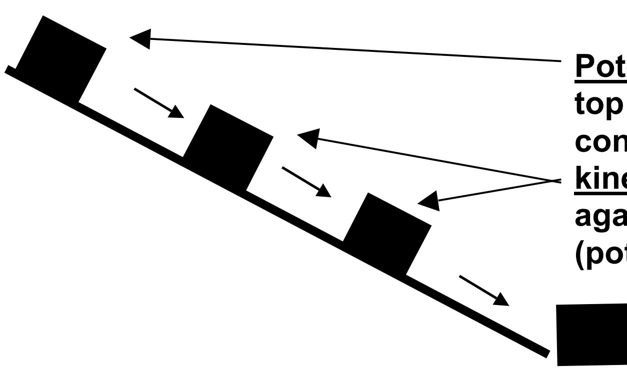
Energy: **is the ability to do work or bring about a change**

What is the study of energy called? **thermodynamics**

The two states of energy and examples of each:

Kinetic energy	**Potential energy**
Energy of motion **Examples are thermal, light, and electrical energy**	**Energy of position or stored energy** **Examples are chemical, gradient, and gravitational energy**

Describe what happened to the energy as the block slid down the ramp.



Potential energy is high at the top of the ramp and is converted to kinetic energy until the block again comes to a halt (potential energy).

First law of thermodynamics: **Energy can change forms and be transferred but it cannot be created or destroyed.**

PowerPoint Presentation 1 Notes

Prior to showing the first slide:

- Show the class a small plastic toy and place it on a table. Place a ramp near the toy and slide a wooden block down a ramp, knocking over the toy at the bottom. Ask the class what knocked over the toy. **(the block, force, gravity)**
- Ask them whether this block (same one sitting next to the toy) would knock over the toy? **(No)**
- Ask them what is different about the two blocks. **(their position, their energy)**

Show slides 1 and 2

Slide 2

- Ask students to think how they would define energy and explain it to someone else.

Slide 3

- Introduce how scientists define the term.

Slide 5

- You've undoubtedly heard of a variety of different kinds of energy: electrical, mechanical energy, light, thermal energy (more commonly but less correctly referred to as heat), chemical energy.
- All of these different forms of energy can be classified as being in one of two states: kinetic energy and potential energy. Define the terms "kinetic energy" and "potential energy" as the energy of motion and stored energy respectively). Introduce the idea that potential energy is stored by virtue of position or arrangement.

Slide 6

- A form of kinetic energy.

Slide 8

- A form of kinetic energy.
- Our cells and therefore our bodies are conductors.

Slide 9

- A form of potential energy.
- Hopefully students will notice: 1) the number and type of atoms are the same but 2) they are arranged differently.
- The energy associated with molecules depends on the locations of electrons, the types of bonds, and rotation about the bonds. Energy is required to break bonds and is released as new bonds are formed. It is, of course, the difference in spatial arrangements of electrons in the atoms of the reactant molecules and the product molecules that will determine whether the energy required to break the bonds in the reactants is greater or less than the energy released as new bonds in the products are formed. (This is what determines if a reaction is exergonic or endergonic).

Slide 10

- A form of potential energy.

Slide 11

- A form of potential energy
- The suspended brick has PE (work had to be done to put it there) and as it falls, the PE is converted to KE. The PE of the water at the top could be converted to KE of a waterwheel, which could be converted to electrical energy.

Slide 13

- Ask what happened as that block moved down the ramp. **(the potential energy was changed to kinetic energy)**
- So what you are telling me is that potential energy can be converted to kinetic energy is that correct? **(Yes).**

Slide 14

- This is part of what physicists refer to as the <u>first law of thermodynamics</u>.

Slide 15

- There is a second part of the first law however that is a little less apparent. Thinking back to our ramp and block, how do you think the total energy before I slid the block compares with the energy after?
  (a) There is less total energy once the block has slid down the ramp?
  (b) There is more total energy once the block has slid down the ramp?
  (c) The amount of energy is unchanged when the block slides down the ramp?
  (Most likely they will say that there is less energy)

Slide 16

- The other part of the first law, that I mentioned earlier, says that ***energy can neither be created nor destroyed so the total amount of energy in the universe remains the same***. If we accept that as true, what is the correct answer to the question I just posed? **(C)**
- Yet most of you thought there was less energy. Why did you think there was less?
  The block isn't up as high, it can't do as much work; the block has stopped moving;
  You are right that the block itself has less energy as it slides down the ramp, but if we accept that the total amount of energy in the universe has not changed, what do you think became of the energy that was in the block at the top of the ramp after it slid to the bottom? **(thermal energy due to friction of block against ramp and the table)**

Slide 17

Questions are (answers are shown above): (could be done as a "Think-Pair-Share" activity).

- Describe the energy transformations that occur as you drive your car.
- Do you have as much gasoline when you get to school as you had when you left home? Why or why not.
- What happened to the energy that was in the combusted gasoline?

Slide 18

- Rubber band -- stretch (kinetic to potential); feel it (heat loss)
- Present a container (can/bottle) of sand. Shake it vigorously and ask students to describe energy transformations. **Potential energy stored in body is converted to kinetic energy of muscle contraction, which is converted to kinetic energy of sand grains in the can.**
- How does the energy in the can and surroundings compared before and after? **According to the first law they are the same.**
- Where do you suppose the energy is when I stop shaking the can? Is there any way that we might be able to measure that? **Energy increases the kinetic energy of molecules, which may be measurable as an increase in the temperature of the sand. Person is also generating heat ... they may feel hot or sweaty.**

(Have students measure temperature of several cans of sand. Give them to students to shake vigorously for about 5 minutes. Measure temperature afterward).

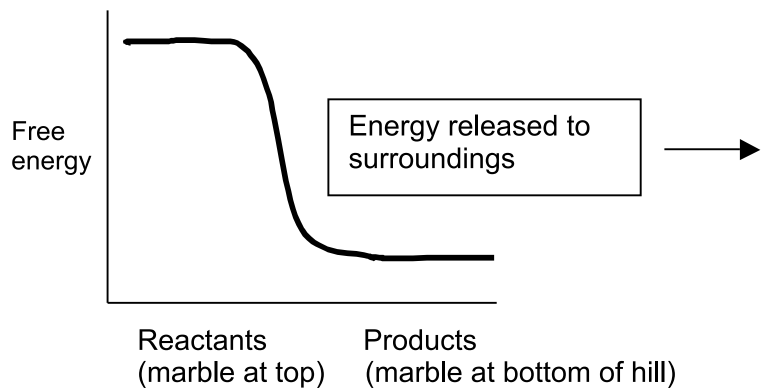
- Remind them that if we had a measure of the total amount of energy at the start and the amount of energy at the end that it would be the same.
- Ask if we let these cans of sand sit for a while, what would happen? **They would cool off.**
- Why? How does the total energy compare? (Think-pair-share) **Heat tends to spread out (Zeroth Law of Thermodynamics); warm sand molecules would increase kinetic energy of surrounding air molecules until they reached thermal equilibrium. While the sand would get cooler, the total energy in the system would remain the same.**

Classroom Exploration – Part 2

Exergonic and Endergonic Reactions: Answers

Instruction: Use PowerPoint presentation 2 (PPT2 – 16 slides) to explore and develop the concepts of the concepts of exergonic and endergonic reactions, and energetically coupled reactions. PPT2 notes are on page 10.

What happened with the bottle of sand? How does this demonstrate the first law of thermodynamics?



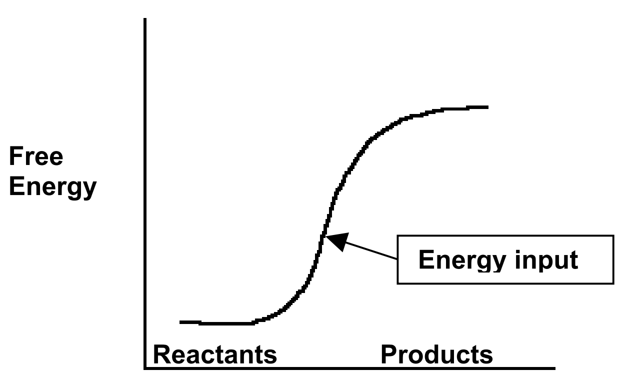
This is a diagram of an **exergonic** reaction. What happens to energy in this type of reaction? **There is a net release of energy during the reaction.**

Give an example of this type of reaction. **Burning a match; powering a car**

Which of the following statements are true about this type of reaction?

- The reactants contain more free energy than the products. **T**
- Energy is given off or released to the surroundings during the reaction. **T**
- The total energy of the system remains the same. **F**

Draw an energy diagram for an **endergonic** reaction.



Complete the following for an endergonic reaction:

- Products have **more** energy than the reactants.
- Reactants are **more** stable than the products
- Energy is **stored** or released during the reaction.
- For this reaction, the energy conversion is:

  Chemical $\longrightarrow$ Light

  Light $\longrightarrow$ **Chemical**

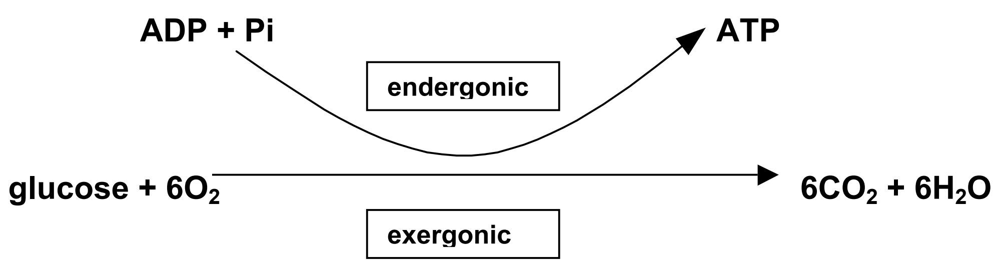
Exergonic or Endergonic?

Gasoline burning	**exergonic**
Hydrolysis of starch	**exergonic**
Active transport	**endergonic**
Translation	**endergonic**

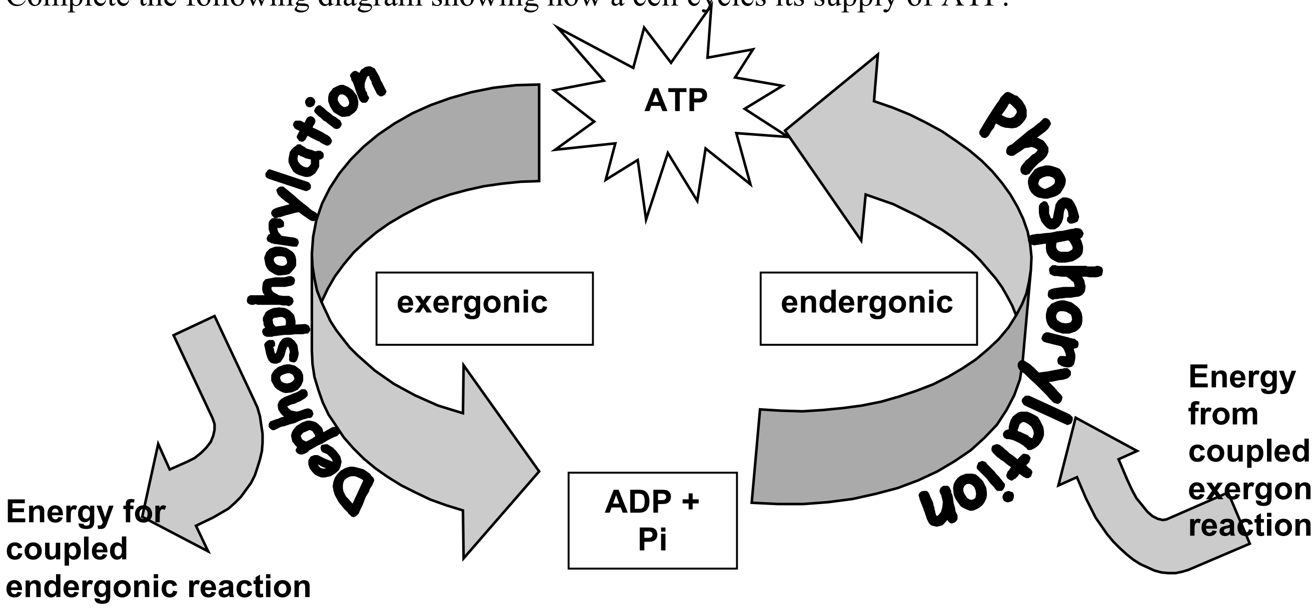
What is a coupled reaction?

A coupled reaction is where an exergonic reaction provides the energy necessary to drive an endergonic reaction.

Give an example of a coupled reaction.



Complete the following diagram showing how a cell cycles its supply of ATP.



Label which reaction is exergonic and which reaction is endergonic.

Instructor's Notes for PowerPoint Presentation 2

Slide 2

- Show a mound of sand and a marble (either real or on slide). Ask students to describe what will happen if we place the marble at the top of the hill. **It will roll downhill. They may describe energy transformations (potential energy to kinetic energy); conservation of total energy.**
- Note that reactions tend to progress spontaneously from positions of instability or greater free energy (top of the hill) to positions of greater stability or lower free energy (bottom of hill).
- Ask what happens to energy in this reaction? (Think-pair-share) **Total energy is constant but energy is released to the surroundings from this system.**

Slide 4

Hopefully the shape of the energy diagram is reminiscent of the sand hill.

Slide 5

Introduction to ATP as a high energy molecule.

Slide 6

All of these statements are true.

Slide 8

- Explain that endergonic is the opposite of exergonic, energy is put into the reaction.
- Have the students draw or explain what the energy curve must look like since it is opposite of the exergonic one they drew in their notes. Give them some time to come up with ideas.

Slide 9

- Have the students also answer the questions on their answer sheet, the last mouse click will put in all the answers (Could also be done using think-pair-share)

Slide 10

Check for understanding. Mouse clicks will put in correct answers.

Slide 11

- Give groups of students a tub of sand, sheets of folded paper and two marbles of equal size. Challenge them to use the energy of rolling one marble down a hill to roll the other marble to the top of a hill.

Slide 12

- Were you able to meet my challenge? **Yes.**
- Where did the second marble get the energy it needed to roll uphill? **From the energy released as the first marble rolled down hill.**
- What kind of reaction is the marble rolling downhill? **Exergonic**
- What kind of reaction is the marble rolling uphill? **Endergonic**

So what you are telling me is that you are using the energy released in the exergonic reaction to drive the endergonic process. Is that correct? **Yes.**

Slide 13

Converting to an equation format.

- Point out that what you start with is shown at the tail end of the arrow (reactants) and what is produced is shown at the pointed end of the arrow (products).
- First equation shows what happens if there is no coupled reaction.

- The second equation shows how in coupled reactions the exergonic reaction provides the energy to drive the endergonic reaction. Emphasize that the two occur together and are opposite of each other energetically (one is exergonic and one is endergonic).
- In generating electricity, our plants take advantage of coupled reactions – where some exergonic process is used to drive the production of electrical current. (Possible extra credit ... describe a process of generating electricity. Describe energy transformations and coupled reactions involved).

Slide 14

- Biological systems rely heavily on coupled reactions. Would you think that food molecules had relatively large amounts or small amounts of energy stored in them? **Large**
- Our bodies break down those large complex food molecules into smaller and simpler molecules of carbon dioxide and water. This is essentially the same thing that happens when food is burned. Have you ever accidentally caught some food on fire? Was it an exergonic or endergonic process? (Alternatively, if the laboratory experiment is completed, ask them whether burning the peanut was an exergonic or endergonic process). **Exergonic. Thermal energy is released.**
- In our bodies, rather than release all that energy as heat, some of it is used to drive coupled endergonic reactions, most commonly the production of ATP.

Slide 15

Another example.

- Ask if muscle contraction is an endergonic or exergonic reaction? (Does it release energy or require energy?)
- Once the students have identified muscle contraction as an **endergonic reaction**, then see if they can come up with an exergonic reaction involving ATP and ADP that could "power" that process.

Slide 16

Having just given examples of both dephosphorylation and phosphorylation, this is a good opportunity to point out the central role that ATP serves in organisms. Point out that the organism has a limited supply of ATP but is able to continuously replenish it by coupling the phosphorylation of ADP to exergonic reactions (such as those in cellular respiration). It is estimated that 150 lb person needs 17 lbs of ATP per hour but has only about 2 oz. available. This means that one's entire ATP supply is being cycled at least once a minute.

Classroom Exploration – Part 3

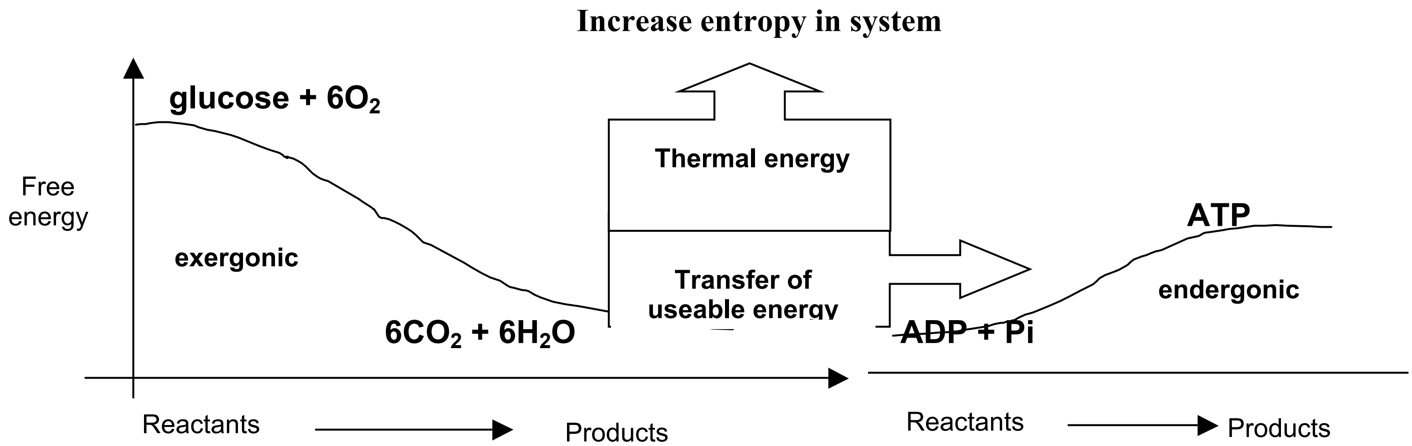
Entropy, the Second Law of Thermodynamics, and Enzymes

Instruction: Use PowerPoint presentation 3 (PPT3 – 21 slides) to explore and develop the concepts of the concepts of entropy, the second law of thermodynamics, and enzymes. PPT3 notes are on page 19.

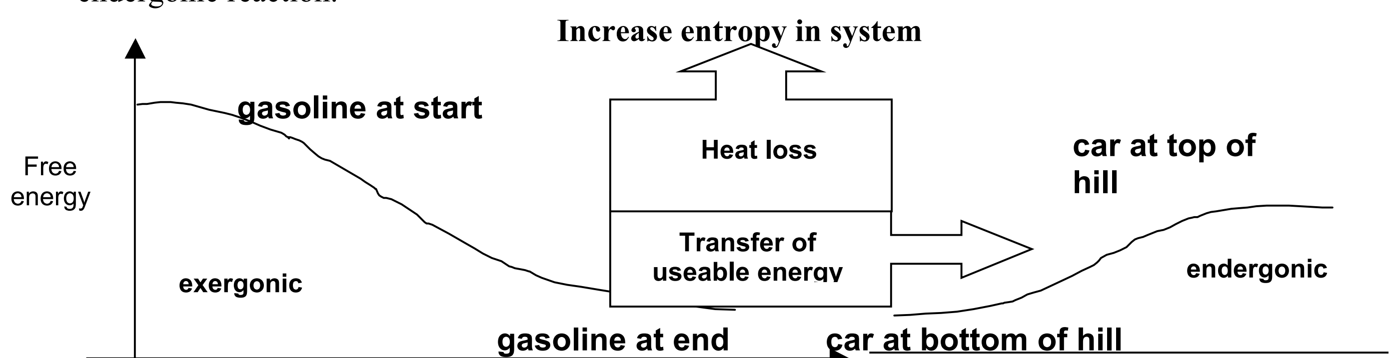
Second law of thermodynamics: **Every energy transfer or transformation increases the entropy, a measure of the disorder of a system.**

Energy Diagrams of Coupled reactions

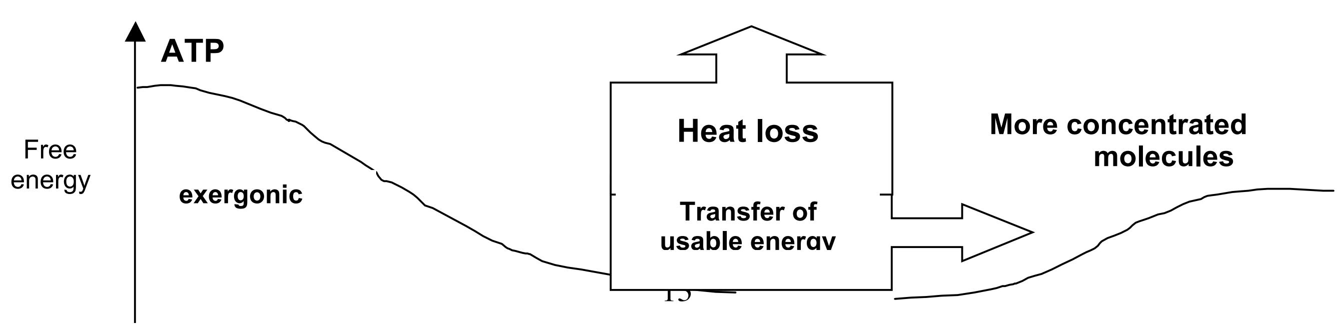
Complete the following showing the energy transfers associated with **cellular respiration**.



Use the following energy diagrams to show the energy relationships involved in the **driving a car uphill.** Label the following in your diagram: gasoline at start, gasoline at end, car at bottom of hill, car at top of hill, heat loss, transfer of usable energy. Label the exergonic and endergonic reaction.



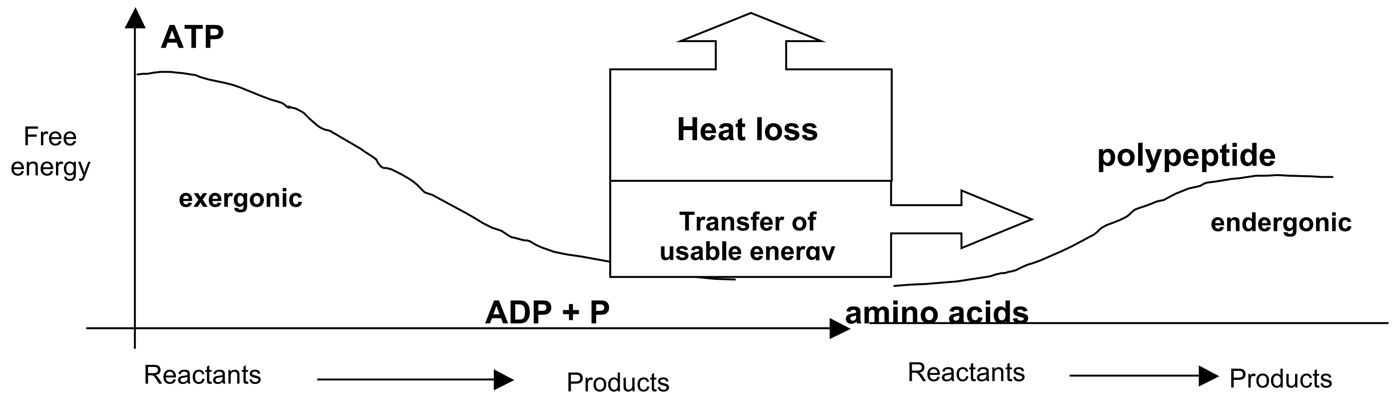
Use the following energy diagrams to show the energy relationships involved in the **active transport**. Label the following in the diagram: random distribution of molecules, more concentrated molecules, ATP, ADP+P, heat loss, transfer of usable energy. Label the exergonic and endergonic reaction.



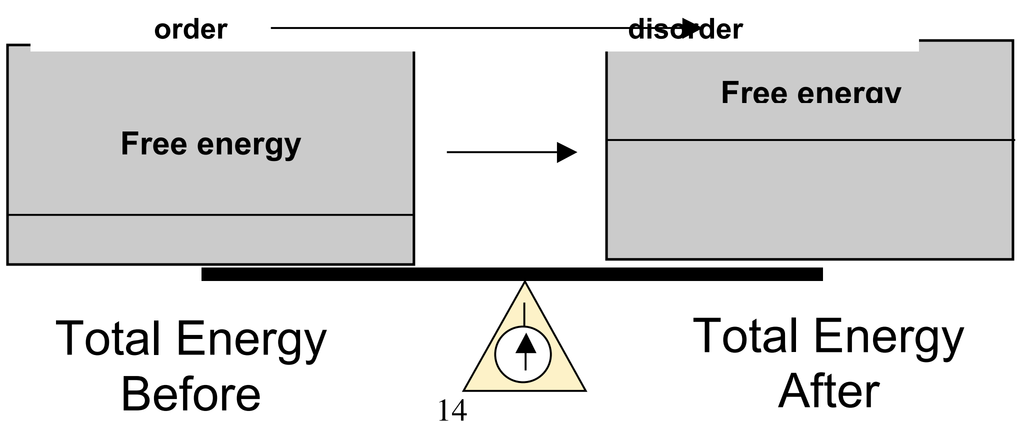
endergonic

ADP + P random molecules

Use the following energy diagrams to show the energy relationships involved in **protein synthesis**. Label the following in the diagram: ATP, ADP + P, amino acids, polypeptide, heat loss, transfer of usable energy. Label the exergonic and endergonic reaction.



Add a second box on the balance to represent what the FIRST law of thermodynamics states.



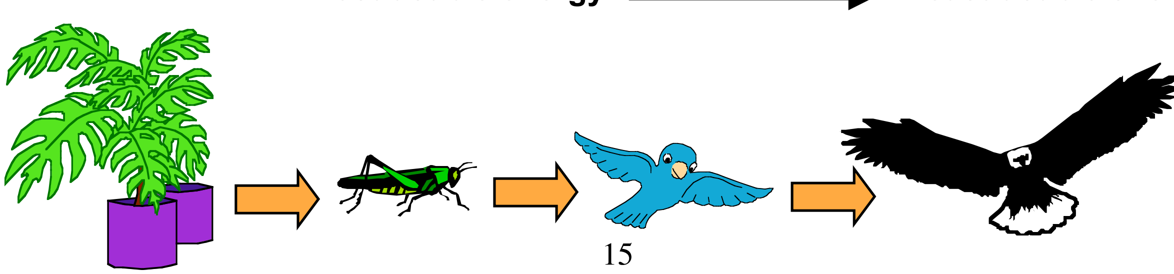
Add to the diagram above to represent the principles of the SECOND law of thermodynamics. **Order to disorder**

What happened with **Newton's Cradle**? How can we explain this result using the laws of thermodynamics?

Living things maintain a complex, highly ordered and unstable structure by a constant input of **energy**. However, with each conversion, some energy is lost as **heat** to the surroundings. This increases the **entropy** of the universe. This is consistent with the **second** law of thermodynamics.

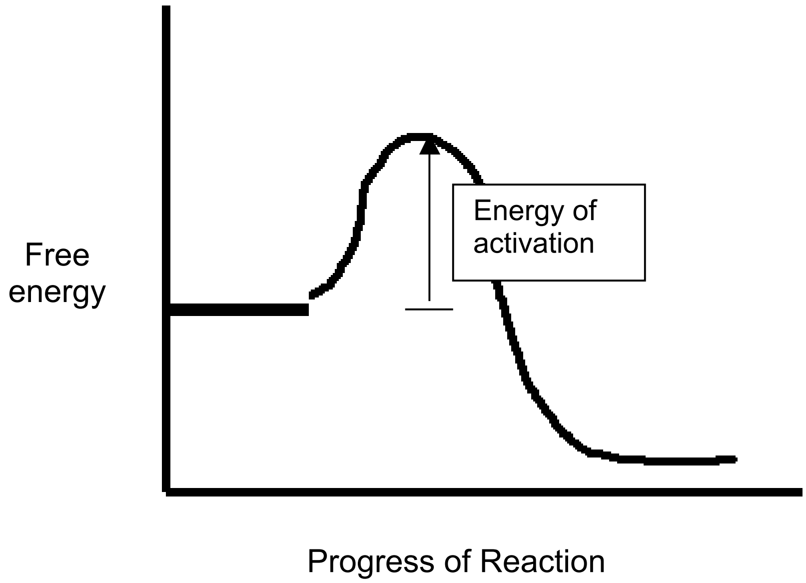
According to the laws of thermodynamics, how should the amount of energy available to herbivores (plant eaters) compare to the amount of energy available to carnivores (animal eaters)?

Most usable energy → **Least usable energy**



Herbivore Carnivores

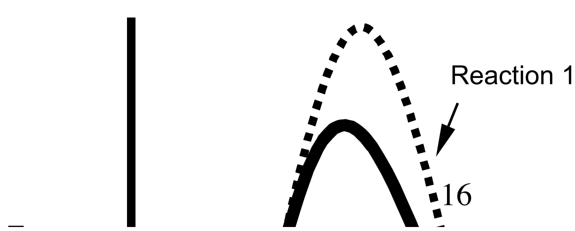
What does the energy diagram look like for the burning of food?



Energy of Activation (E_A)
Input of energy to start a reaction

Why is E_A needed?
E_A is needed to make the reactants less stable by weakening or breaking some of the bonds and allowing for rearrangement into products.

Which reaction would occur more quickly? Explain your answer. **Reaction 2 because it requires less activation energy, so more reactions can occur over a set period of time.**



How is E_A provided in the laboratory?
In the laboratory is provide as heat.

Why is this a problem for cells?

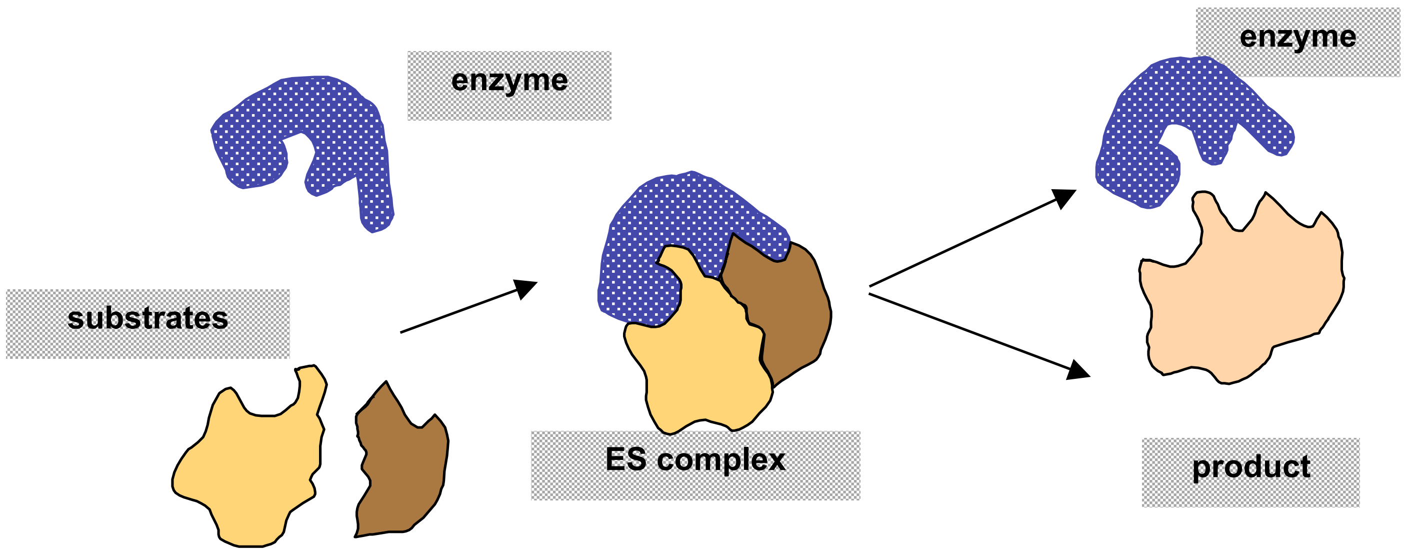
- **Elevation of temperature would denature cellular proteins and nucleic acids, killing cells – and the organism.**

- **The elevated temperature would increase the rate of all reactions in cells.**

What makes it possible for cells to carry out reactions quickly at physiological temperatures?
In place of heat, cells use enzymes to speed up (catalyze) specific cellular reactions at physiological temperatures.

Most enzymes are **proteins**.

What is special about the shape of an enzyme? **The shape is specific such that the active site recognizes a single shaped substrate.**

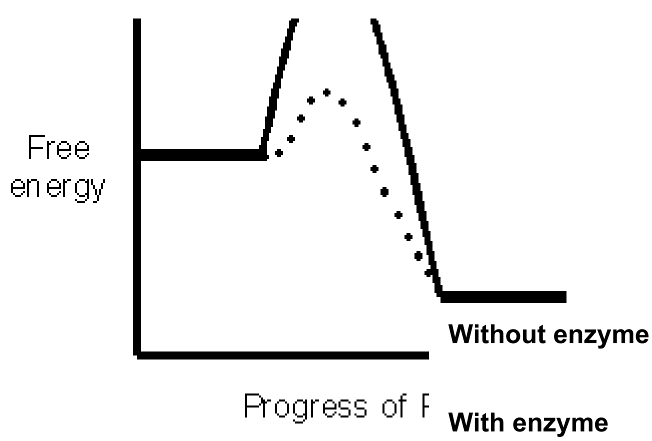


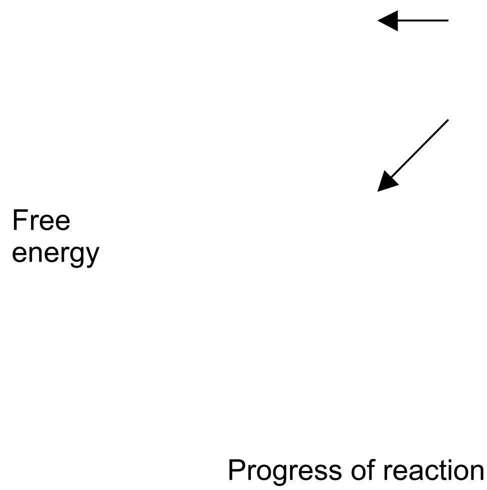
How do enzymes speed (catalyze) reactions?

1. **Enzymes lower the activation energy.**

2. **Place stress on chemical bonds such that they break more easily.**

How does this change the energy diagram?




Free
energy
Progress of reaction

Instructor's Notes for PowerPoint Presentation 3

Slide 2

- Let's go back to our marbles for a moment. Were you able to get the second marble to roll up as high a hill as the first rolled down? **No.**
- Why not? **Not all of the energy was available to do work.**
- Where is the rest of the energy? **In increased kinetic energy of sand, the marble etc.**

Good. This points out the **second law of thermodynamics**. It says that in any energy transformation, the amount of usable (free) energy in the universe is constantly decreasing.

Slide 3

This is designed to reinforce the students' ability to recognize exergonic and endergonic energy diagrams, to visualize the energy transfers associated with coupled reactions, and to illustrate the second law of thermodynamics.

Slide 4

Application questions. Answers are shown on subsequent slides.

Slide 8

Illustrates the major concepts of the first and second laws of thermodynamics.

Slide 9

Application question for laws of thermodynamics.

- Bring out Newton's cradle and a grid to stand behind. Have students predict outcome and ask volunteers to share their reasoning. Then actually do the experiment.
  Correct choice is the third one because of the second law.
  [Alternatively this could be done with a marble and a cut pipe. Roll marble from one side to other. Ask students to predict what will happen **(Should only have enough energy to get part way up the other side)**]
- Optional follow-up question: How would the total energy compare before and after dropping the marble?
  A .Total energy would increase
  B. Total energy would decrease
  C. Total energy would remain the same.

Slide 10

This tendency for reactions to progress spontaneously from unstable and complex to simple and stable is part of what is described by the **second law of thermodynamics.** It says that the disorder (or what physicists sometimes call entropy) of the universe is constantly <u>increasing</u>.
Then how do biological things exist? The molecules that make us up are highly ordered and therefore unstable. What keeps us from falling apart?

- Give groups of students 5 Styrofoam cups. Say that these represent the molecular components of a cell. Ask them to stack them in a more orderly way to represent the complex organization of a cell).
- How were you able to do that? **Had to invest energy**
- How stable is what you have built? Try to carry it intact to the front of the room.
  (Not very stable. High free energy, low stability)
- Suppose this represents the structural organization of a cell. In order for the cell to remain alive it must maintain this structure. Over time what is going to happen to this structure. **It is going to tend to fall apart.**

Slide 11

- What is going to allow the cell to remain structured? **An investment of energy; endergonic processes.**
- Yes, we are dependent on a constant input of energy from our surroundings to maintain our order. Where do humans get this input of energy? **From our food**

If we cease to get that external energy then we die and our structure falls apart.

Slide 13
Application question. Only about 10% of the energy from one trophic level is transferred to the next. The remaining 90% includes heat loss and also energy remaining in uneaten or undigestable parts of food.

Slide 14
This slide relates the lecture material to the laboratory experiment (on calorimetry) and introduces the idea of "Energy of Activation."

Slide 15
- Why is E_A needed? (Shown in overlapping textboxes on sequential mouse clicks):
  1. Reactants are stable molecules that satisfy the bonding requirements of their atoms.
  2. Need energy (E_A) to break some of these bonds and allow for rearrangement into products.
  3. Without E_A, complex molecules would immediately fall apart into simpler and more stable molecules.
- How would this affect living things? **Living things could not exist since their structures depend on complex organic molecules that would be energetically unfavored.**

Slide 16
Ask students to think about and discuss this question (think-pair-share) before showing the answer.

Slide 17
This slide is to help students realize the importance of chemical reactions to living organisms and the need for enzymes.
(Question and answers shown on sequential mouse clicks). Allow students to reflect and discuss before revealing the answer.
- Why can cells not use elevated temperature as a way to supply the needed E_A for reactions? **Heat would denature proteins and thus kill the cell and heat would increase the rate of all reactions at once.**

Slide 20
Have students predict how the energy diagram would look before showing the next slide.

Laboratory

Materials and equipment required

per group:

Bunsen burner
book of matches
pair of metal forceps

metal probe
10 ml. Graduated cylinder
ring stand and test tube clamp
thermometer
6 regular test tubes
ice cube
culture dish

per class:
digital balance (weighing to the hundredth of a gram)
samples (20 of each): peanuts, walnuts halves, corn chips, Honeycomb cereal, oyster crackers, wooden applicator sticks)
roll of aluminum foil
dishpan of soapy water
access to the internet

Working in Cooperative Groups

Your team must work as a **cooperative group**; that is, each member of the team has a contributing role. Therefore, before your team starts its exercises and experiments, you need to define and assign cooperative roles.

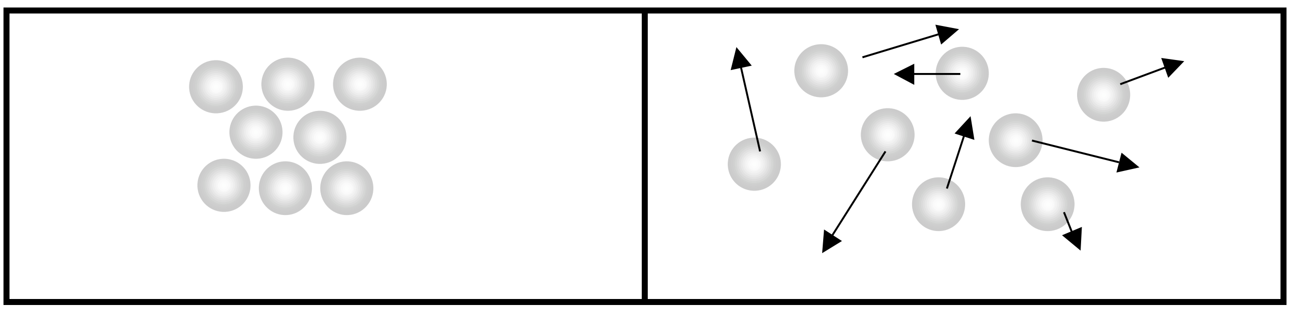
Name	Description of Cooperative Role
1)	***Team leader*** – Keeps track of team progress. Makes sure everyone contributes to the team plan and that decisions are made together.
2)	***Recorder*** – Records all data and observations. Makes sure the team discusses and answers all questions for the laboratory report.
3)	***Materials Procurer*** – Makes sure that equipment and materials are where they are needed.
4)	***Materials Procurer*** – Makes sure that equipment and materials are where they are needed.

Laboratory Activity

Observing Energy Transformations

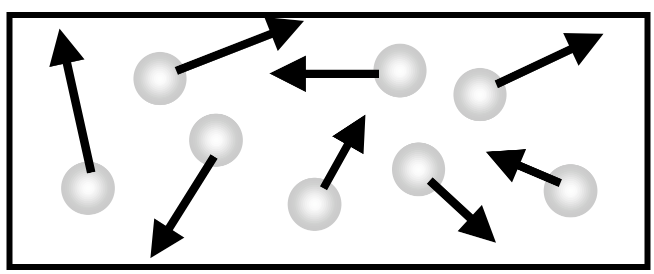
1. Obtain a piece of ice. Place it in a culture dish. Allow it to sit at room temperature for several minutes and describe any changes that you observe.

2. Shown in the left frame below is a simple schematic diagram of eight water molecules in an ice cube. In the right frame, draw a diagram showing these eight water molecules after the ice has been sitting for several minutes.



(Solid water, ice) (After sitting)

3. Draw a diagram of showing what the water molecules would look like after being heated over a flame.



(After heating)

4. Why is there a difference between the pictures? That is, what type of change took place? Did this change require energy? If so, what is the source of this energy? Explain.

Molecules are moving faster, a heat change (transfer of thermal energy). Yes because the molecules are moving faster; they must have acquired energy. Transfer of energy from other molecules that were moving more rapidly.

Laboratory Exercise

Food Calorimetry: Measuring the Energy in Food

Working in your lab group, carry out the following food calorimetry exercise using a peanut as the "food sample."

PROCEDURE:

1. Pour 10 mls of water into a test tube.
2. Mount the test tube in a test tube clamp and place a thermometer in the test tube.
3. Measure the initial temperature (T_i) of the water and record it in the table below.
4. Zero the balance. Measure the mass of the food item on a small square of aluminum foil, and record the value in the table below (be as precise as possible). Try to obtain a sample such that its mass (along with the foil square) is between 1.0 and 1.5 grams. Record the initial mass (M_i) in the table below).
5. Hold the food with a pair of metal forceps.
6. Ignite the food by placing it in the flame of a match or Bunsen burner. (Be sure the flame is not near the test tube of water).
7. As soon as possible after the food ignites, place the burning food beneath the test tube. The flame should touch the tube (and will likely cause the tube to blacken). Continue to hold the burning food under the test tube, repositioning it as necessary to keep the flame directly under the tube, until the flame goes out. If the temperature should reach 80°C, extinguish the flame prematurely.
8. After the temperature of the water stops rising, record its final temperature (T_f) in the table below.
9. Scrape any food residue from the forceps onto your square of aluminum foil. Measure the final mass (M_f)of the food residue and record it in the table below (be as precise as possible).
10. Calculate the change in temperature and the mass of food burned by subtracting the initial from the final values.

Food Item	Final Temp (T_f) (°C)	Initial Temp (T_i) (°C)	Change in Temp (T_f-T_i)	Initial Mass (M_i) (grams)	Final Mass (M_f) (grams)	Mass of food burned (M_f-M_i) (grams)
Peanut						

Things to Ponder:

1. Looking back at page 13, which of your diagrams illustrate the **water molecules** at the beginning and end of this procedure.
   Second and third drawings.

2. Describe the transfer of energy that occurs in this experiment.
   Chemical energy of food transferred to thermal energy, which increases the kinetic energy of the water molecules.

3. What is the source of the energy that raised the temperature of the water?
   Energy stored in food; chemical energy

   Is this energy source kinetic or potential energy? **Potential energy**

4. Why was it necessary to ignite the food with a match or Bunsen burner? Why didn't it start to combust spontaneously?
   Molecules do not spontaneously combust. They need an initial input of energy (activation energy) to get the process started.

5. Why was it important to keep the match or Bunsen burner away from the tube of water?
   So that we are only measuring the energy from the food rather than the energy from the burning gas/match.

Calculating Calories:

We can use this technique to compare the amount of energy in different foods. Calories are a measure of energy. A calorie is defined as the amount of energy to raise the temperature of 1 gram of water by 1°C.

1. To calculate the energy (calories) released by combusting a food item, multiply the mass of the water used (1 ml = 1 g of water) by the change in temperature. This gives you the number of calories that were transferred to the water from the burning food sample.

   Change in temperature x Grams of water used = Number of calories released

   ____________ x ___________ = ___________

2. In order to be able to fairly compare the calories from one sample to another, we need to adjust this value for the amount of food burned. Determine the amount of food actually burned by subtracting the mass of the peanut "after" from the mass of the peanut "before."

   Mass of food before − Mass of food after = Mass of food burned

   ___________ − ___________ = ___________

3. Take the calories calculated in step #1 and divide by the change in mass calculated in step #2. This gives you the number of calories per gram of peanut.

   Number of calories released ÷ Mass of food burned (g) = calories (c) per gram of food

__________ ÷ __________ = __________

4. Dietary calories (C) are actually kilocalories. To relate the caloric value you just calculated to dietary calories (C), divide your calories (c) per gram of peanut by 1000.

calories (c) per gram of food ÷ 1000 = Calories (C) per gram of food
__________ ÷ 1000 = __________

Record this value in the table at the bottom of this page.

A more concise equation for this calculation would be

$$\text{Calories per gram (C/g)} = \frac{(\text{grams of water used} \times \text{change in temperature})}{(\text{mass of food burned}) \times 1000} \times \frac{\text{Cal}}{\text{g °C}}$$

We are going to use this technique to compare the energy found in the following foods:

- peanut
- corn chip
- pecan or walnut
- Honeycomb™ cereal
- oyster cracker

Before conducting this experiment, **predict** how these foods will compare in their stored energy. Explain your reasoning.

Greatest energy

Least energy

Measure the energy found in the foods listed in the table below by using the procedure outlined on pages 14. Use a clean test tube for each measurement.

Calculate the Calories per gram by following the steps on page 15-16 or using the equation on page 16.

Food Item	Final Temp (T_f) (°C)	Initial Temp (T_i) (°C)	Change in Temp (T_f-T_i)	Initial Mass (M_i) (grams)	Final Mass (M_f) (grams)	Mass of food burned	Calories (C) per gram

						$(M_f - M_i)$ (grams)	
Peanut							
Corn Chip							
Pecan or Walnut							
Honeycomb cereal							
Cracker							

Things to Ponder:

1. How do these foods compare in their caloric content? Based on your data, rank them from highest to lowest calories per gram. How do your results compare to your predictions?

2. What might explain any differences observed in the caloric content of these different foods?
   Different nutritional make-up; different percentage of water; experimental error

Comparing Results to Nutritional Information

Let's compare the energy content you have measured with the caloric values listed in the nutritional information for these foods. We could find this data on the packaging or in a nutritional database. We are going to use a nutritional database available on the internet. You will need to go to the following web page:

http://www.nat.uiuc.edu/mainnat.html

1. Select the age and gender of someone in your group from the pull-down menu in "Step 1."

2. Type the name of the first food in Step 2 and click on the “Add food” button. The database will list all the foods with that name in its descriptor. Select the one from the list that best describes the food you used in the experiment, and click on “Add selected food button.” The peanuts used were oil-roasted; the pecans/walnuts were dried.

3. Select “Gram” from the pull down menu of serving sizes and type “1” in the box for the number of servings. Click on the “Add this amount” button.

4. You should see the food listed on the “Personal Diet List.” Fill in your next food in the space above the list and repeat steps 2-4 until you have listed all of the foods tested.

5. Once you have listed all of your foods, click on the “Analyze foods” button. This will give you the nutritional analysis of all of the foods combined.

6. Click on the “Display nutrients for individual foods” button to get an item analysis. Print out a copy of this page for your group. **(Copy attached).**

Complete the following table to compare the experimentally determined caloric values and the nutritional values.

Food Item	Calories/gram (Experimental) (from page 17)	Calories/gram (Nutritional) (from database)
Peanut		
Corn Chip		
Pecan or Walnut		
Honeycomb Cereal		
Cracker		

Things to Ponder:

1. How do these five foods compare in their caloric content according to the **nutritional information**? Rank them from highest to lowest.
   Pecan (or walnut), peanut, corn chip, cracker, cereal

2. How does this ranking compare to that determined experimentally? How does this ranking compare to your predictions (page 16)?

3. Consider the highest calorie foods tested versus the lowest calorie foods tested. What do you think might explain the difference in their caloric content? Do you have any evidence to support your idea?
   Foods that are highest in calories are also highest in fat content.

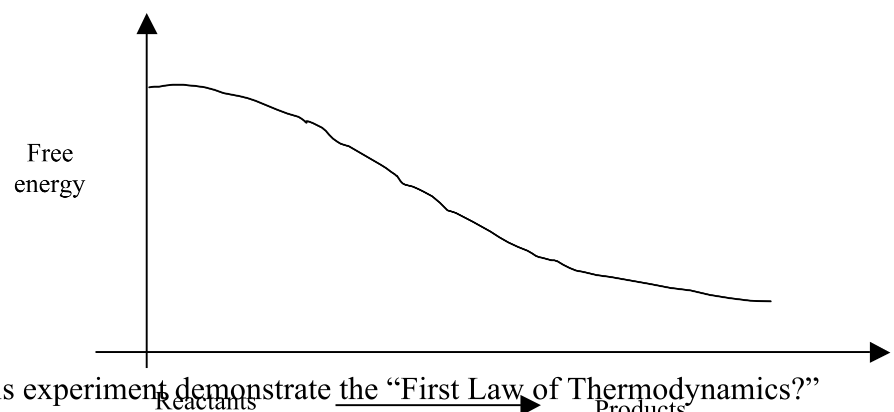
4. How does the caloric content measured experimentally compare to the nutritional caloric content?
   Only a small percentage of nutritional caloric content is measured experimentally.

5. Excluding the possibility that the nutritional information is wrong, what could explain any difference observed?
   Not all of the energy from the food is being transferred to the water)

6. Looking over the experimental procedure you've used, do you see any steps where there is an unmeasured release of energy from the food? Can you think of any way to modify the procedure to increase the accuracy or efficiency of your energy measurements?
   Make sure that the flame is beneath the tube; minimize the amount of food that is burned in the Bunsen burner flame.

7. Would you classify the combustion of the food items as an exergonic or endergonic reaction? What is your evidence?
   Exergonic; energy is being released from the food and is increasing the kinetic energy of the water molecules and gas molecules in the air.

8. Sketch a diagram illustrating the energy levels of the reactants and products for the combustion of food. Do the products have more or less energy than the reactants?



9. How does this experiment demonstrate the "First Law of Thermodynamics?"
   Energy is being converted from one form to another.

10. How does this experiment demonstrate the "Second Law of Thermodynamics?"

When the reaction is over there is less usable energy in the system; much of the energy in the food molecules has been converted to thermal energy.

11. Traditionally the caloric content of foods was measured in a device called a "bomb calorimeter." A bomb calorimeter is a closed system containing plenty of oxygen in which some material is ignited electrically and allowed to combust completely. The energy in the sample is determined by the change in temperature in the chamber.

    How is a bomb calorimeter different from your experimental set-up? What would make its measurement of caloric content more accurate than yours?
    It is a closed system so all of the energy released from the food is retained within the instrument, whereas with our procedure a significant amount of thermal energy is lost and unmeasured.

12. Today most caloric determination of foods is <u>not</u> done using a bomb calorimeter. Instead the nutritional content of the food is analyzed (that is, the amount of carbohydrates, fats and protein) and these values are multiplied by the corresponding number of calories per gram for these types of molecules.

    Proteins and carbohydrates have approximately 4 calories per gram, and fats have approximately 9 calories per gram.

12. For example, 1 gram of a Snickers candy bar contains 0.1 g of protein, 0.22 g of fat and 0.60 grams of carbohydrate. Based on the caloric information for proteins, fats and carbohydrates listed above, how many calories would you expect 1 g of Snickers to contain? (Show your work)
    4.78 Calories/gram

    Look up the caloric content of 1 g of Snickers candy bar in the nutritional database. How does this value compare with the caloric information calculated?
    4.55 Calories/gram ... very close

    One Snickers bar has a mass of 61 grams. How many calories would a Snickers bar contain? (Show your work)
    4.78 C/gram x 61 g = 292 C or 4.55 C/gram x 61 g = 278 C

"Burning Food" in Biological Systems

In this experiment, you have oxidized the food and converted its stored energy to thermal energy. In the human body, food is enzymatically oxidized (you have probably heard of people refer to us "burning our food") by a process called **cellular respiration**. In this process, the food is oxidized more slowly, and while some of the energy is released as heat, some of it is transferred in coupled reactions to other energy-storing molecules such as the molecule of ATP.

It is estimated that, at maximum, cellular respiration transfers about 37% of the energy of food to ATP and the remainder is lost as heat. That ATP provides the necessary energy for other endergonic reactions in the organism.

1. How does cellular respiration relate to the "first law of thermodynamics?"
   In cellular respiration, energy is converted from one form to another [chemical to other forms of chemical energy and heat energy]. The total amount of energy is, however, unchanged.

2. How does cellular respiration relate to the "second law of thermodynamics?"
   In the process only a maximum of 37% of the potential energy of glucose is converted to a usable form of energy; the other 63% is converted to heat.

3. Suppose that cellular respiration were much more efficient. Supposed that 75% of the calories in food were transferred to ATP. If your cells' need for ATP remained the same, how would this change your daily caloric requirements?
   You would need to ingest fewer calories since they would be used more efficiently.

4. Suppose that cellular respiration only transferred 5% of the energy to ATP. If your cells' need for ATP remained the same, how would this change your daily caloric requirements?
   You would need to ingest more calories to supply your cells' need for ATP.

5. There are drugs and certain physiological situations, which decrease the efficiency of cellular respiration. How would these conditions affect the organism's body temperature? How would these conditions affect the organism's use of food and stored energy reserves? **Since a lower percentage is being transferred to ATP, a greater percentage would be lost as heat. Therefore you might expect the body temperature to elevate. In order to meet the body's need for ATP, the organism would need to metabolize more food. This also would contribute to an even more elevated temperature.**

Calorimetry of Other Materials

1. Repeat the calorimetry procedure using a wooden stick as your sample. Based on your results, what is the Caloric content per gram of wood?

2. Assuming that the calorimetric determination for the wood is comparable in its efficiency of transfer as it was with your other samples, what would you estimate to be the actual Caloric content of wood? (Show your work).
   ~5-10 x measured value

3. If there were a nutritional label on a package of wooden sticks (for example, popsicle sticks, or toothpicks), it would read "Calories 0." How might you explain the discrepancy between the label and your results? **The energy stored in a toothpick (cellulose) is not usable by the enzymes of the human body. Therefore, those calories are not of any nutritional value.**

4. The "Nutrition Facts" information from a box of All Bran cereal is shown below. Calculate the calories per serving based on this nutritional information.

Nutrition Facts

Serving Size	_ cup (31 g; 1.1 oz)
Servings per package	About 17
Amount per Serving	
Total Fat	1 gram
Total Carbohydrate	24 grams
Fiber	11 grams
Sugars	6 grams
Other carbohydrates	7 grams
Protein	4 grams

The calories per serving listed on the box are 80. How does this compare with your calculation?

Calories will be higher from calculation if fiber is included in the carbohydrate total

Total carbohydrates 24 g x 4 cal/gram = 96 calories
Total fat 1 g x 9 cal/gram = 9 calories
Total protein 4 g x 4 cal/gram = 16 calories
Total calories based on calculation = 121 calories per serving

How might you explain any difference observed?

The calories from fiber (like the toothpick) are not usable by the human body and therefore are not included in the nutritional caloric values).

Total digestible carbohydrates 13 g x 4 cal/gram = 52 calories
Total fat 1 g x 9 cal/gram = 9 calories
Total protein 4 g x 4 cal/gram = 16 calories
Total calories based on calculation = 77 calories per serving

Homework Assignment

ENERGY AND THERMODYNAMICS: ANSWERS

1. Shown below are the calorimetry data collected for a sample of Food A. Calculate the Calories (kilocalories) per gram based on this data. (You will need to refer to the formula on page 16).

Food Item	Final Temp (T_f) (°C)	Initial Temp (T_i) (°C)	Change in Temp (T_f-T_i)	Final Mass (M_f) (grams)	Initial Mass (M_i) (grams)	Mass of food burned (M_f -M_i) (grams)	Calories (C) per gram
Food A	87	23	**64**	0.36	1.0	**0.64**	**1**

$$\text{Calories per gram (C/g)} = \frac{\text{(grams of water used x change in temperature)}}{\text{(mass of food burned) x 1000}} \times \frac{\text{Cal}}{\text{g °C}}$$

Calories/gram = (10g x 64 °C)/ (0.64 g x 1000) x Cal/g°C
Calories per gram = 640 /640 = 1

2. If you looked at the nutritional information for Food A on its packaging you would expect the Calories listed to be **b. higher than** the Calories calculated above.

   This is because
   b. when a food is burned in this apparatus some of its energy is not transferred to the kinetic energy of the water molecules.

2. The nutritional composition of Food A and a second food (Food B) is listed below:

FOOD	**PROTEINS**	**CARBOHYDRATES**	**FATS**
A	5%	10%	85%
B	10%	80%	10%

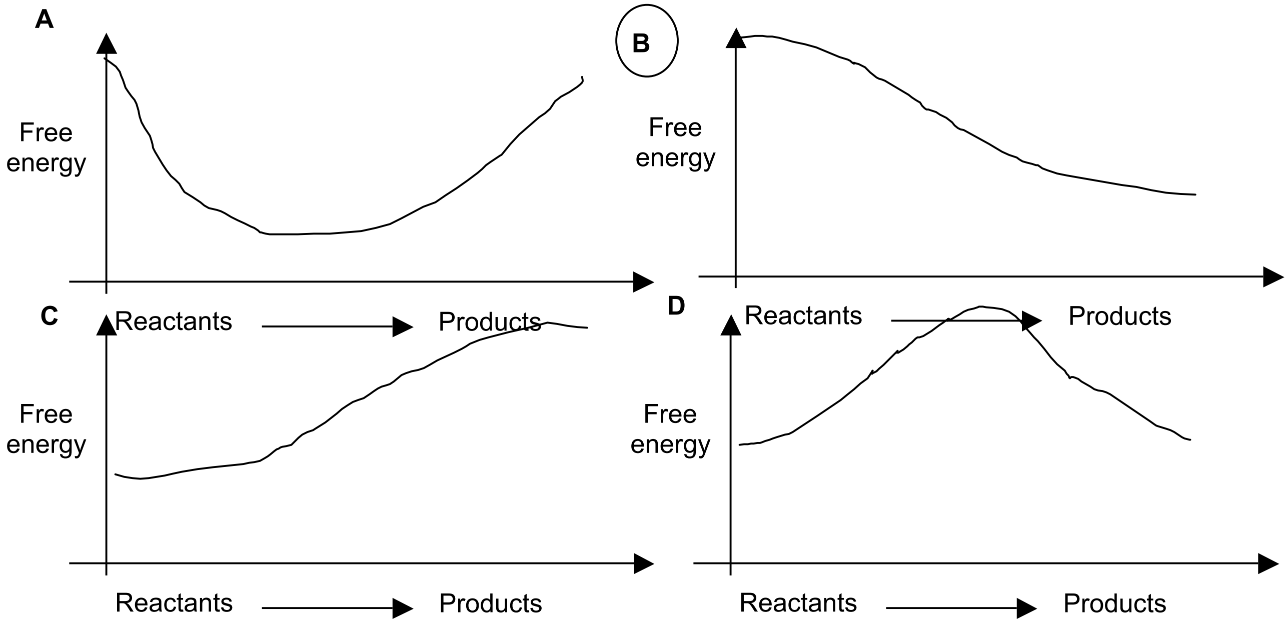
If you used equally sized samples of the two foods, which one would you expect to heat the test tube of water to a higher temperature? **A**

Which of the following best explains your reasoning:

a. **Food A because it contains a greater percentage of fat than B, and fats store more energy (calories) than proteins or carbohydrates.**
b. Food B because it contains a greater percentage of carbohydrates than A, and carbohydrates store more energy (calories) than proteins or fats.
c. Food B because it contains a greater percentage of protein than A, and protein stores more energy (calories) than carbohydrates or fats

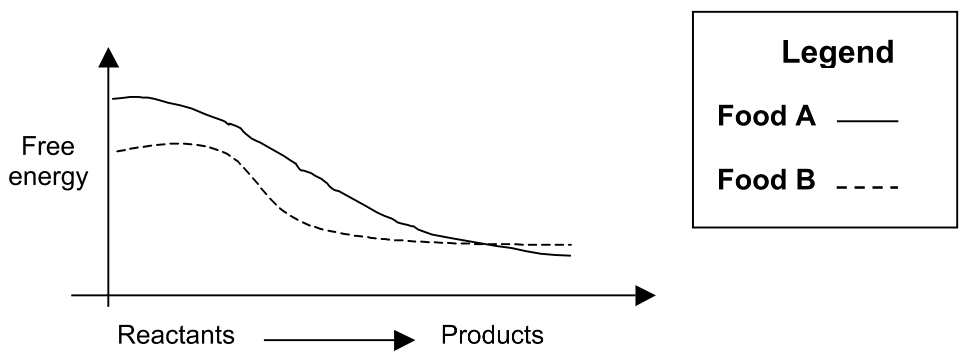
4. Which one of the following best describes the flow of energy observed in the calorimetry experiment?
   a. As the food changes chemically, its potential energy is transformed to increased kinetic energy of water molecules.

5. Which one of the following energy diagrams best illustrates what happens when food burns?



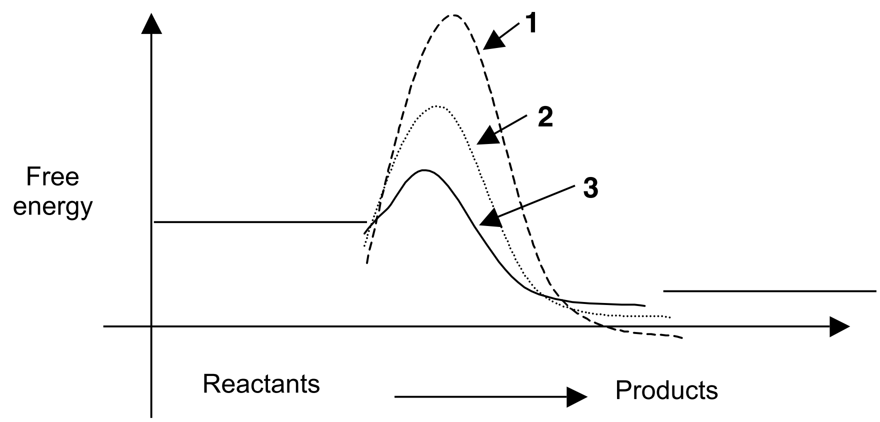
What term describes this kind of reaction? ____**exergonic**____

6. In the space below, show how the energy diagrams for the combustion of Food A and Food B would differ (see problem #1). (Distinguish between the graph for Food A and Food B in some way [for example with different colored or different kinds of lines]. Indicate which line is which in the legend of the chart).



7. The combustion of food did not occur without a match or flame because the molecules in food must have enough energy to reach an unstable transition state. The energy required to reach this transition state is called **Energy of activation**
(no abbreviations please)

8. How do food molecules reach the transition state in the body?
   a. Our body has a furnace that can provide the needed spark.
   b. The thermal energy released by other reactions going on in the body provides enough energy.
   c. Enzymes supply the energy required and thus help the molecules over the "hurdle."
   d. Enzymes lower the energy input required to reach a transition state.



9. As illustrated in the graph above, a certain chemical reaction has three different E_As depending on the conditions. The three E_As are 5 kcal/mole, 13 kcal/mole and 18 kcal/mole. Which of the lines shown above represents an E_A of 18 kcal/mole?
   a. line "1"
   b. line "2"
   c. line "3"
   d. none

   Assuming that all other conditions are the same, the rate of the reaction should be fastest under what conditions?
   a. The reaction should go fastest with the E_A shown by line "1".
   b. The reaction should go fastest with an E_A shown by line "2".
   c. The reaction should go fastest with an E_A shown by line "3".
   d. Since it is the same reaction, it should go at the same rate in all three conditions.

10. In general, how does the process of combusting food in the laboratory differ energetically from metabolizing that same food in your body?
   a. The amount of energy released in converting foods to carbon dioxide and water is less in the body than in the laboratory.

b. The amount of energy released in converting foods to carbon dioxide and water is greater in the body than in the laboratory.

c. The amount of energy released in converting foods to carbon dioxide and water is the same in the body as in the laboratory; however, in the body not all of it is released immediately as heat.

d. The amount of energy released in converting foods to carbon dioxide and water is the same in the body as in the laboratory; however, in the body none of the energy is released as heat

e. The process is the same whether it occurs in the body or in the laboratory.

11. In 1894, an American chemist Wilbur Olin Atwater built a sealed room in which he could place human or animal subjects. The walls were designed such that there was no heating or cooling of the room from the outside; however, any change in thermal energy in the room would heat or cool room temperature water running through pipes in the walls. Consequently he could very precisely measure any change in water temperature and calculate the corresponding energy change.

i. Dr. Atwater calibrated his device with a kerosene lamp. The longer the lamp burned the higher the temperature of the water in the pipes was. Describe how this illustrates the first and second laws of thermodynamics.

First law: Energy is transformed from one form to another (chemical energy of kerosene converted to increased kinetic energy of water molecules).
Second law: The amount of entropy has increased; the water molecules are moving faster and the kerosene has been combusted to smaller and more stable molecules.

ii. Suppose Dr. Atwater placed a human subject in the chamber at 10 pm and left him there asleep for eight hours. When he measured the temperature of the water at 8 am the next morning, it was warmer than the night before. How can you best explain the change in temperature?

a. The subject must have been burning a kerosene lamp otherwise the temperature would not have increased.

b. Metabolism of food in the subject's body releases thermal energy.

c. The temperature of the room was cooler in the morning than the night before.

d. The subject must have had a fever during the night; that is the only way the water could have increased in temperature.

iii. Suppose the subject was left in the chamber for an additional eight hours and instructed to ride a stationary bicycle during that time. What would you expect to happen to the temperature of the water in the pipes?

a. The temperature of the water should stay the same

b. The temperature of the water should decrease

c. The temperature of the water should increase more than it did when the subject was at rest.

d. The temperature of the water should increase at the same rate as it did when the subject was at rest.

iv. Which one of the following best explains your reasoning.

a. Exercise makes people sick and feverish.
b. When humans exercise they perspire, and this would cool off the room and lower the water temperature.
c. The human body maintains a constant temperature regardless of its activity so the temperature of the water should not change.
d. Activity requires more ATP than rest; therefore, the cells would carry out cellular respiration at a faster rate and release more thermal energy during the hours of exercise.
e. Humans have an innate metabolic rate that they are born with. A person's metabolism alone determines how many calories he or she "burns" each day.
f. All of the stored energy used would be converted to ATP to give the person's muscles the necessary energy to exercise; there would be no heat released

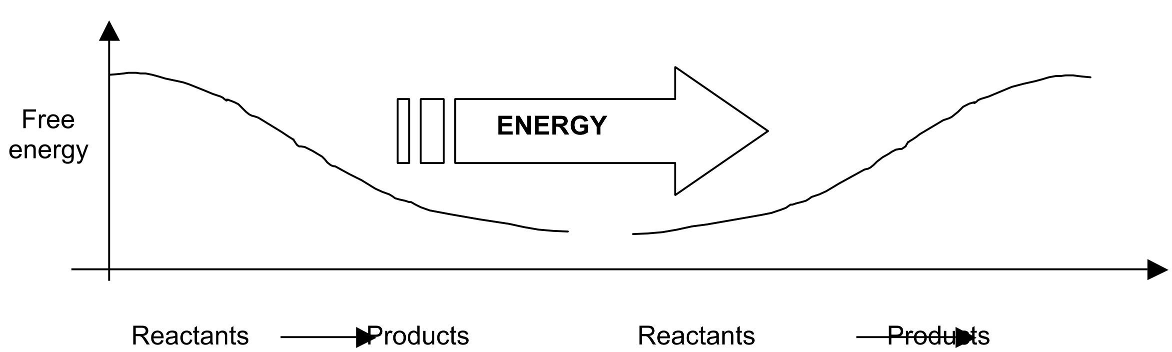
v. Listed below are several forms of exercise and the kcalories "burned" per hour by an average person engaging in each.
Stair climbing machine – 381
Jogging – 445
Jumping rope – 636

A person doing which one of these activities in the Atwater chamber would cause the greatest increase in water temperature? **Jumping rope**

12. Calorimetry data shows that one mole of glucose molecule releases approximately 686 kcals when combusted. Since there are 7 kcals/mole of ATP, this is the equivalent of 98 moles of ATP. Use the laws of thermodynamics to explain why cellular respiration cannot produce 98 moles of ATP per glucose molecule metabolized.

The second law of thermodynamics requires that the amount of free energy decrease with each energy transformation; therefore not all of the energy in glucose is captured in ATP. About 60% is lost as heat.

13. According to the laws of thermodynamics, the following coupled reactions are energetically impossible. Explain why.
See #12



Background Information

Misnomers and Misconceptions

1. Chemistry refers to exothermic and endothermic reactions. Biology texts refer to exergonic and endergonic reactions. ***Exothermic and exergonic do NOT mean the same thing.*** While in both cases, "ex" means "out" and "ender" means "into," the "thermic" terms refers to changes in <u>thermal energy</u> (ΔH), whereas, the "ergonic" terms refer to changes in <u>free energy</u> (ΔG). So chemists talk about reactions that either release or take up thermal energy while biologists tend to focus on the release or increase in free energy in the system.

   Free energy is a measure of the instability of the system. In general, larger, complex molecules will tend to be more unstable than smaller, simpler molecules. The second law of thermodynamics tells us that reactions tend to proceed spontaneously toward greater disorder (entropy) or toward greater stability (lower free energy). That is exergonic reactions are product-favored and endergonic reactions are product-unfavored.

Many exothermic reactions are also exergonic and many endothermic reactions are also endergonic, but not all. For example, melting ice is an endothermic reaction (requires heat from the surroundings) but it is exergonic (product-favored; spontaneous). This is because while heat energy must be invested to break hydrogen bonds holding the ice into a lattice formation, by breaking up the crystalline array, the disorder of the system has increased. This increase in entropy exceeds the heat energy invested so the overall free energy of the system has decreased. The equation for free energy change is:

$$\Delta G = \Delta H - T\Delta S$$

The change in free energy of a reaction is equal to the change in enthalpy (ΔH) (heat of reaction) minus temperature times the change in entropy (ΔS). Temperature amplifies the effect of the entropy term since an increase in temperature would increase the degree of disorder. The ΔG of a spontaneous (product-favored) reaction is negative.

ΔH	ΔS	ΔG
– (exothermic)	+ (increase in disorder)	– (product-favored; exergonic)
+ (endothermic)	– (increase in order)	+ (product-unfavored; endergonic)
– (exothermic)	– (increase in order)	temperature dependent – (product favored [exergonic] at low T) +(product unfavored [endergonic] at high T)
+ (endothermic)	+ (increase in disorder)	temperature dependent + (product unfavored [endergonic] at low T) – (product favored [exergonic] at high T)

So ice melts spontaneously at room temperature because the energy required to break the hydrogen bonds is less than the increase in entropy at that temperature resulting in a negative ΔG.

2. ***It is inappropriate to refer to chemical energy being stored in chemical bonds. Energy is NOT released as bonds are broken and stored as bonds are formed.*** Breaking bonds costs energy. Forming new bonds releases energy. In any chemical reaction, there will be bonds broken and new bonds formed. What determines if a reaction releases or requires energy is the difference in those amounts of energy. In an energy-yielding reaction, there is more energy released as new stronger bonds of the product are formed than was invested in breaking the weaker bonds of the reactants. Conversely, if more energy is invested in breaking the bonds of the reactants than is released as the new bonds of the product are formed, the reaction requires energy.

   For example, the combustion of glucose is exergonic and exothermic, not because the bonds of glucose are strong and release energy when broken, but rather because the energy required to break the bonds of glucose and oxygen is less than the energy released as the very stable molecules of carbon dioxide and water are produced. Glucose is a high energy molecule because it has relatively high free energy not because it has high energy bonds. Similarly, biologists often refer to the bond attaching the third phosphate to the molecule of ATP as a high energy bond; it is in fact a relatively weak bond of a very unstable molecule (one with high free energy). Dephosphorylation increases the entropy of the system and releases free energy.

It is probably a misnomer to refer to chemical bonds as high energy or low energy bonds because that reinforces the misconception that that energy is released when bonds are broken. It is more appropriate to refer to strong or weak bonds; that terminology reinforces the concept that energy is required to break bonds.

3. ***Substances do NOT contain heat.*** Substances contain **thermal energy**. Thermal energy refers to the **total** kinetic energy of the particles in a substance. The more vigorous the movement, the greater the thermal energy and the higher the temperature. Temperature is a measure of the **average** kinetic energy of the particles. For same sized samples of the same type of matter, the higher the thermal energy the higher the temperature. For different-sized samples of the same type of matter, the thermal energy depends on the amount of substance and on the temperature. For example, a bathtub full of water at 40°C has more thermal energy than a cup of hot water at 70°C because it has more total water molecules and more total molecular motion. However, the average kinetic energy of the water molecules in the cup of hot coffee is higher than the average kinetic energy of the water molecules in the bathtub, hence the coffee has a higher temperature.

   Heat is NOT a form of energy. Heat is the transfer of thermal energy between two substances resulting either in an increase in the kinetic energy (and hence temperature) of one substance or in an increase in the potential energy of one substance (e.g., as occurs with a change of state)...