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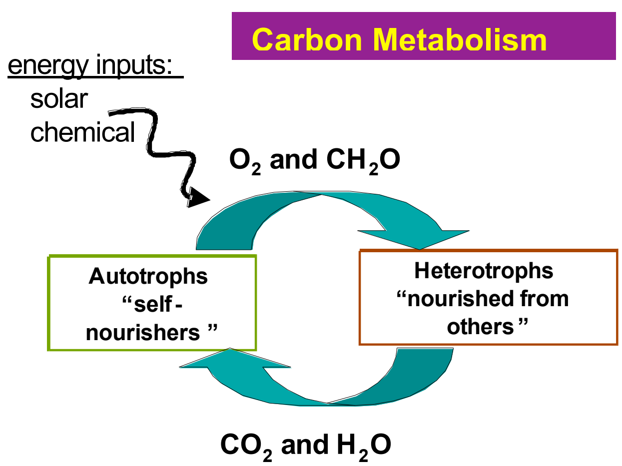
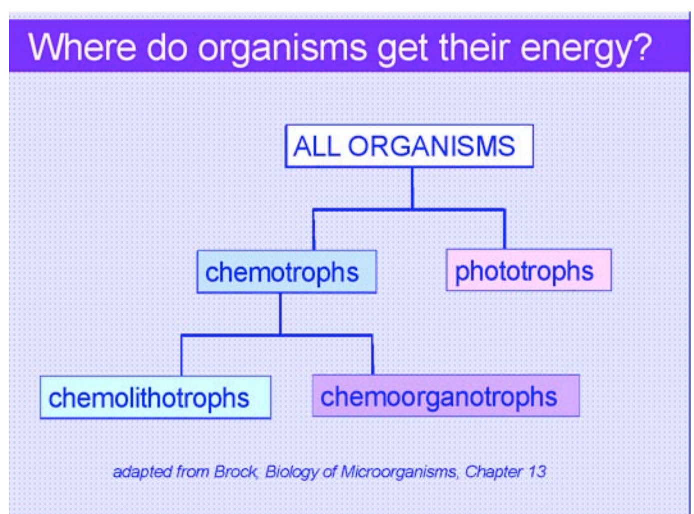
Lecture 3: How to be Alive
Carbon and energy transformations

Nature has put itself the problem of how to catch in flight light streaming to earth and to store the most elusive of all powers in rigid form."
Mayer, 1842, discovered law of conservation of energy

Summary





Organisms can be broadly classified by how they obtain their energy and carbon

Living organisms can be generally categorized by their primary sources of carbon, reducing power (electrons), and energy. Typically whether these carbon, energy and electron sources are organic, or inorganic, guides the classification. The different types of metabolisms found in these diverse organisms, that differentially oxidize or reduce different organic and inorganic chemicals in the environment, is what drives biogeochemical cycles in the biosphere. Their integrated activities balance oxidation and reduction reactions in the environment, and keep the system cycling between the oxidized and reduced forms of organic and inorganic materials.

A. Autotrophs

These “self-nourishers” typically get their energy from the sun (photoautotrophs), or from reduced inorganic compounds (chemoautotrophs a.k.a. chemolithotrophs). They get their carbon for growth and production of new cells from CO_2.

The energy generating reactions produces ATP’ and NADPH’’, which provide stored biochemical energy and reducing power forbiosynthesis and production of new cells. For oxygen-generating photosynthetic organisms (like plants and cyanobacteria), the light-requiring reaction that generates energy is known as the Hill, or “light reaction”. There are a number of different ways that organism can incorporate, or “fix” inorganic CO2 into organic material. In plants, the Calvin Cycle, is common biochemical pathway, and uses the stored energy and reducing power (ATP and NADPH) to convert CO_2 to CH_2O (sugar).

1. Oxygenic Photosynthesis (produces O_2)

Who? Plants, cyanobacteria, eukaryotic algae
C Source? CO_2
Energy Source? Sunlight
Electron Donor? H_2O
(the oxygen from the water used in photosynthesis, is what produces the O_2 we breath !)
Where? In aerobic, light conditions

$$CO_2 + H_2O + h\nu \longrightarrow CH_2O + O_2$$

2. Anoxygenic Photosynthesis (doesn’t produce O_2)

Who? Bacteria (e.g. Purple sulfur bacteria, green sulfur bacteria)
C Source? CO_2
Energy Source? Sunlight
Electron Donor? H_2S, H_2, Fe^{2+}
Where? In anaerobic, light conditions

$$CO_2 + 2\,H_2S + h\nu \longrightarrow CH_2O + 2\,S + H_2O$$

3. Chemosynthesis

Who? Chemoautotrophic bacteria, aka chemolithoautotrophs (“rock eaters”)
C Source? CO_2
Energy Source? Reduced inorganic compounds (CH_4, H_2, NH_4, H_2S, Fe^{2+})
Electron Donor? Reduced inorganic compounds
Where? In microaerobic or anaerobic, dark conditions

Sulfur oxidizing bacteria:	$H_2S \rightarrow S \rightarrow SO_4^{2-}$
Methanotrophs:	CH_4 (methane) $\rightarrow CO_2$
Nitrifying bacteria:	$NH_4^+ \rightarrow NO_2^- \rightarrow NO_3^-$
Iron oxidizing bacteria:	$Fe^{2+} \rightarrow Fe^{3+}$

*ATP = adenosine triphosphate. (ADP = adenosine DI phosphate)

**NADPH = nicotinamide adenine dinucleotide phosphate

B. Heterotrophs

These organisms ("nourished by others") get their energy and carbon by oxidizing ("burning") reduced organic compounds, eg organic matter. ATP and NADH*** are produced, which can then be used elsfor biosynthesis, growth and the production of new cells. (***NADH = nicotinamide adenine dinucleotide (chemically similar to NADPH, NADH is oxidized to facilitate ATP production, while NADPH is associated with biosynthesis).

1. <u>Aerobic respiration</u>

Who? Aerobic eukaryotes and prokaryotes
C Source? CH_2O (sugars, amino acids, organic acids, other organic compounds)
Energy Source? CH_2O
Electron Acceptor? O_2
Where? Aerobic conditions

These reaction is essentially the reverse of the Calvin cycle. O_2 is the final electron acceptor. Plants also carry out this reaction to get energy for their growth and metabolic processes.

$$CH_2O + O_2 \longrightarrow CO_2 + H_2O$$

2. <u>Fermentation</u>

Who? Eukaryotes and prokaryotes
C Source? CH_2O
Energy Source? CH_2O
Electron Acceptor? organic compounds (part of the energy source gets oxidized, the other part reduced)
Where? Anaerobic conditions

This is only the first part of respiration and results in partial breakdown of glucose. The products are organic acids or alcohols (*e.g.*, lactic acid, ethanol, acetic acid) rather than CO_2.

3. <u>Anaerobic respiration</u>

Who? Prokaryotes only
C Source? CH_2O
Energy Source? CH_2O
Electron Acceptor? Oxidized inorganic compounds (SO_4^{2-}, Fe^{3+}, NO_3^{+}, etc.)
Where? Anaerobic conditions

Very similar to aerobic respiration, except that O_2 is not the final electron acceptor. Instead, another oxidized compound such as SO_4^{2-}, NO_3^{-}, or CO_2 is the final electron acceptor.

Iron reducing bacteria:	$Fe^{3+} \rightarrow Fe^{2+}$
Denitrifying bacteria:	$NO_3^- \rightarrow NO_2^-$
	$NO_2^- \rightarrow N_2$
Sulfate reducing bacteria:	$SO_4^{2-} \rightarrow S \rightarrow H_2S$
Methanogens:	$CO_2 \rightarrow CH_4$ (methane)

Overview of Life on Earth

The energy that drives all life processes is organized around oxidation/reduction reactions. Ultimately on Earth today, oxygenic photosynthesis, and energy from the sun, fuels the entire biosphere. Oxygenic photosynthesis produces (by the splitting of water as a reducing agent) one of the most powerful oxidants known – oxygen. The biosphere on the contemporary Earth runs largely on the carbon produced by CO2 fixation by oxygenic photosynthesis, and on the free energy difference between O_2 and organic carbon, which heterotrophs use to fuel their metabolism. The autotrophs synthesize glucose using solar or chemical energy, which is broken down through respiration (either their own or that of the organisms that eat them) to provide the energy necessary for “biological work”. Redox reactions are central to all of these energy transformations, and the resulting flows of electrons manifest themselves, collectively, in the form of global biogeochemical cycles. The activities of bacteria keep these cycles moving. For example, the chemosynthetic bacteria oxidize many essential elements in the process of getting the energy required to reduce CO_2. Certain anaerobic bacteria in turn reduce these compounds in the process of anaerobic respiration — i.e., they use them as an electron acceptor in the absence of oxygen. **This keeps the element cycles cycling maintaining balanced amounts of oxidants and reductants necessary for diverse metabolic processes. This keeps the system from “running down” energetically. Stay tuned for section on Biogeochemical Cycles.**

Study Questions:

- What are the relative light, oxygen and sulfide levels in each layer of a Winogradsky column after it has gotten established and is in steady state? What types of organisms dominate each layer? What are the energy and carbon sources for each kind of organism?
- What microbes form the base of this food web in hydrothermal vent ecosystems? Could this system persist in the absence of photsynthesis on the surface of the earth? Why or Why not?
- What reaction does Ribulose bisphosphate carboxylase catalyze? Why has “Rubisco” been called the most important protein on Earth?
- What is the difference between a chemoorganotroph and a chemolithotroph? Or between an autotroph and a heterotroph? Or between a chemotroph and a phototroph?
- If a lake is covered in algae, how do anoxygenic photosynthetic bacteria, which live underneath the algae, manage to obtain sufficient light to carry out photosynthesis?
- The article, “Can deep bacteria live on nothing but rocks and water?” is 10 years old. Can you find more recent research that provides more substantial evidence for this type of microbial metabolism?

APPENDIX

This is the same information given above, organized slightly differently & in more detail

Modes of Nutrition - Some basic definitions

An organism needs a source of carbon, plus energy (ATP), plus reducing power (NADH). These may all come from the same source (e.g. glucose provides all three), or they may come from different sources:

Where does the carbon come from?

a) Organic molecules – heterotrophs

b) Inorganic - mainly CO_2 = autotrophs

Where does the energy come from?

a) Chemical reactions (redox reactions) - chemotrophs

b) Light - phototrophs

What molecule is the electron donor?

a) Organic molecules - organotrophs

b) Inorganic (e.g., H_2O, H_2, Sulfur) - lithotrophs

What molecule is the electron acceptor ?

a) O_2 = aerobic respiration

b) Oxidants other than O_2 (SO_4, NO_3, FeIII) = anaerobic respiration

METABOLIC DIVERSITY of Energy Sources (Reductants) and Sinks (Oxidants)

CHEMOLITHOAUTOTROPHS - Examples

Bacterial group	Typical species	Metabolic process	Electron donor	Electron acceptor	Carbon source	Product
Hydrogen-oxidizing bacteria	Alcaligenes eutrophus	H_2 oxidation	H_2	O_2	CO_2	H_2O
Carbon monoxide - oxidizing bacteria	Pseudomonas carboxydovorans	CO oxidation	CO	O_2	CO_2	CO_2
Ammonium-oxidizing bacteria	Nitrosomonas europaea	Ammonium oxidation	NH_4^+	O_2	CO_2	NO_2^-
Nitrite-oxidizing bacteria	Nitrobacter winogradskyi	Nitrite oxidation	NO_2^-	O_2	CO_2	NO_3^-
Sulfur-oxidizing bacteria	Thiobacillus thiooxidans	Sulfur oxidation	S, S_2O_32-	O_2	CO_2	SO_4^{2-}
Iron-oxidizing bacteria	Thiobacillus ferrooxidans	Iron oxidation	Fe^{2+}	O_2	CO_2	Fe^{3+}
Methanogenic bacteria	Methanobacterium thermoautotmphicum	Methanogenesis	H_2	CO_2	CO_2	CH_4
Acetogenic bacteria	Acetobacterium woodii	Acetogenesis	H_2	CO_2	CO_2	CH_3-COOH

Groups of bacteria able to use inorganic electron donors for growth ("chemolithoautotrophs").

Image by MIT OpenCourseWare.

ANAEROBIC RESPIRERS - Examples

Bacterial group	Typical species	Metabolic process	Electron acceptor	Reduction products(s)
Denitrifiers	Pseudomonas denitrificans	Nitrate respiration	NO_3^-	N_2, N_2O, NO_2^-
Sulfate reducers	Desulfovibrio vulgaris	Sulfate respiration	SO_4^{2-}	S^{2-}
Sulfur reducers	Desulfuromonas acetoxidans	Sulfur respiration	S^0	S^{2-}
Methanogenic bacteria	Methanobacterium thermoautotrophicum	Carbonate respiration	CO_2	CH_4
Acetogenic bacteria	Acetobacterium woodii	Carbonate respiration	CO_2	CH_3-COOH
Succinogenic bacteria	Wolinella succinogenes	Fumarate respiration	Fumarate	Succinate
Iron reducers	Pseudomonas GS-15	Iron respiration	Fe^{3+}	Fe^{2+}

Physiological groups of bacteria able to grow under anaerobic conditions using external electron acceptors for electron transport

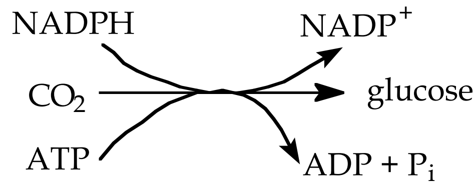
Image by MIT OpenCourseWare.

Autotroph

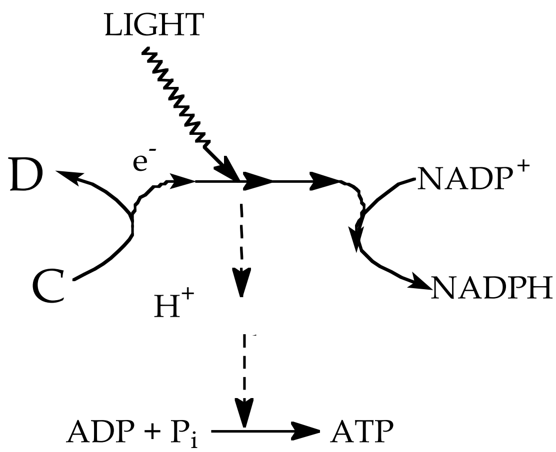
(Quantities of compounds omitted for simplicity.)

"Dark Reactions"

(common to all)



Photosynthesis



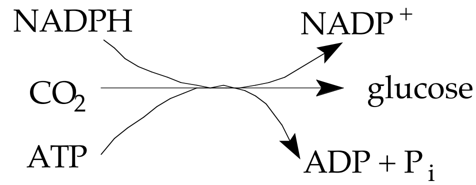
Type	**C**		**D**
oxygenic (plant)	H_2O	$\Rightarrow$	O_2
anoxygenic	H_2S	$\Rightarrow$	S, SO_4^{2-}

Autotrophs, continued:

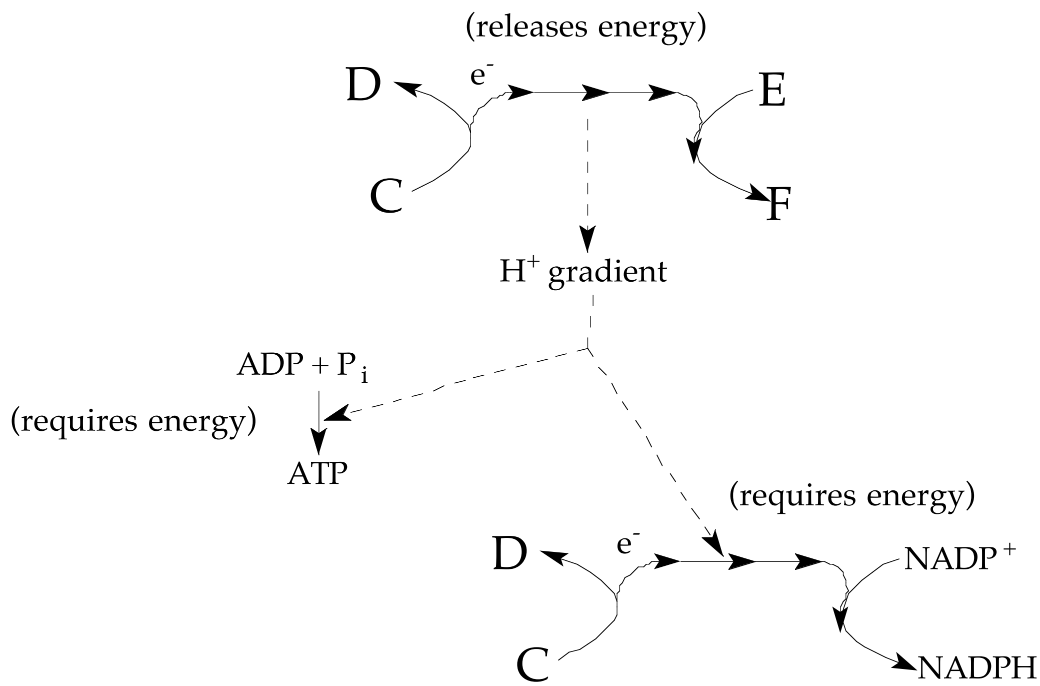
(Quantities of compounds omitted for simplicity.)

"Dark Reactions"

(common to all)



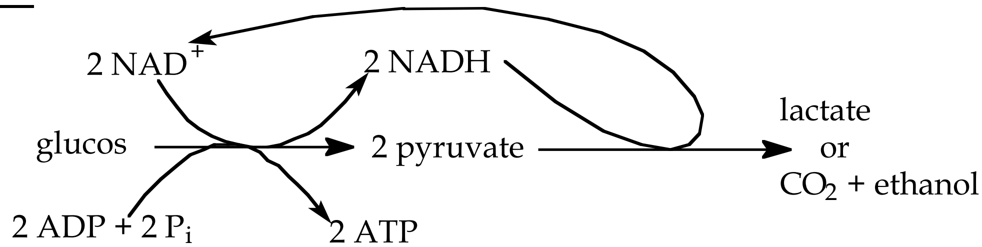
Chemosynthesis



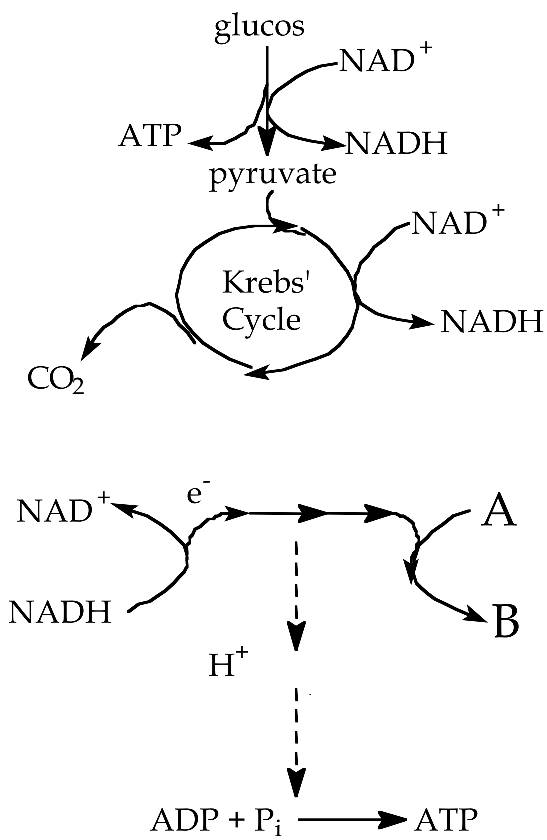
Type	**C**		**D**	**E**		**F**
sulfur-oxidizing	H_2S	$\Rightarrow$	S, SO_4^{2-}	O_2	$\Rightarrow$	H_2O
	H_2S	$\Rightarrow$	S, SO_4^{2-}	NO_3^-	$\Rightarrow$	N_2O
nitrifying	NH_3, NO_2^-	$\Rightarrow$	NO_3^-	O_2	$\Rightarrow$	H_2O

Heterotroph

Fermentation



Respiration (Quantities of compounds omitted for



Type	**A**		**B**
aerobic	O_2	$\Rightarrow$	H_2O
sulfate-	SO_4^{2-}	$\Rightarrow$	H_2S or S
denitrifyin	NO_3^-	$\Rightarrow$	NO, N_2, N_2O, NH_3

1.018J / 7.30J Ecology I: The Earth
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