Chapter 9
Cellular Respiration
Harvesting Chemical Energy

AP Biology

Harvesting stored energy

- Energy is stored in organic molecules
  - heterotrophs eat food (organic molecules)
    - digest organic molecules
      - serve as raw materials for building & fuels for energy
    - controlled release of energy
      - series of step-by-step enzyme-controlled reactions
  - "burning" fuels
    - carbohydrates, lipids, proteins, nucleic acids

Harvesting energy stored in glucose

- Glucose is the ideal molecule
  - catabolism of glucose to produce ATP

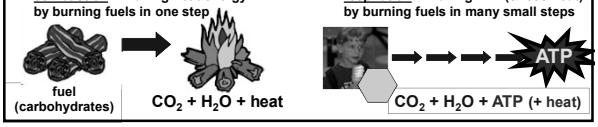
respiration

glucose + oxygen → carbon + water + energy dioxide

$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + ATP + heat$

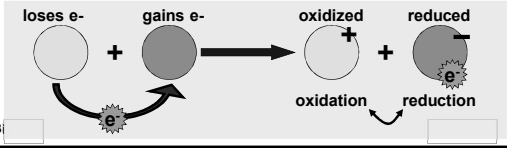
combustion = making heat energy by burning fuels in one step

respiration = making ATP (& less heat) by burning fuels in many small steps



How do we harvest energy from fuels?

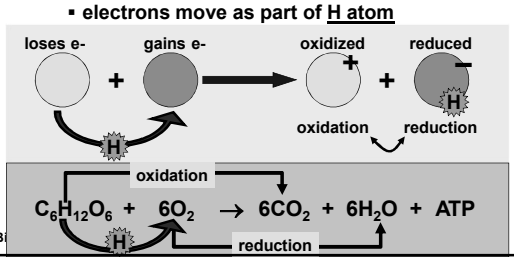
- Digest large molecules into smaller ones
  - break bonds & move electrons from one molecule to another
    - as electrons move they carry energy with them
    - that energy is stored in another bond, released as heat, or harvested to make ATP



AP Bi

How do we move electrons in biology?

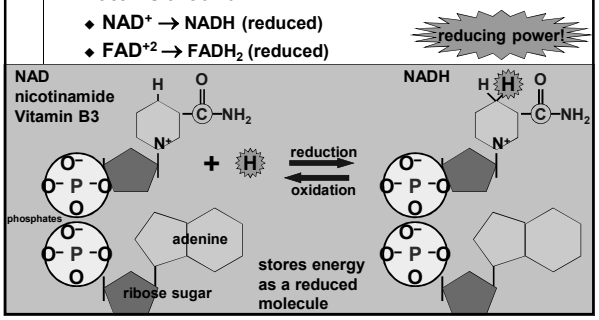
- Moving electrons
  - in living systems, electrons do not move alone
    - electrons move as part of H atom



AP Bi

Moving electrons in respiration

- Electron carriers move electrons by shuttling H atoms around
  - $NAD^+ \rightarrow NADH$ (reduced)
  - $FAD^{+2} \rightarrow FADH_2$ (reduced)



Coupling oxidation & reduction

- Redox reactions in respiration
  - release energy as breakdown molecules
    - break C-C bonds
    - strip off electrons from C-H bonds by removing H atoms
      - $C_6H_{12}O_6 \rightarrow CO_2$ = fuel has been oxidized
    - electrons attracted to more electronegative atoms
      - in biology, the most electronegative atom? $\rightarrow O_2$
      - $O_2 \rightarrow H_2O$ = oxygen has been reduced
    - release energy to synthesize ATP

oxidation

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + ATP$$

reduction

Oxidation & reduction

- Oxidation
  - adding O
  - removing H
  - loss of electrons
  - releases energy
  - exergonic
- Reduction
  - removing O
  - adding H
  - gain of electrons
  - stores energy
  - endergonic

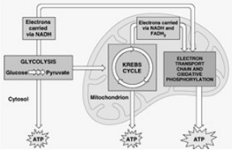
oxidation

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + ATP$$

reduction

Overview of cellular respiration

- 4 metabolic stages
  - Anaerobic respiration
    - 1. Glycolysis
      - respiration without O_2
      - in cytosol
  - Aerobic respiration
    - respiration using O_2
    - in mitochondria



$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + ATP \text{ (+ heat)}$$

Chapter 9.
Cellular Respiration
STAGE 1: Glycolysis

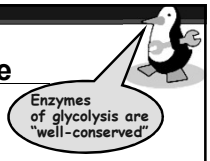
Glycolysis

- Breaking down glucose
  - "glyco – lysis" (splitting sugar)

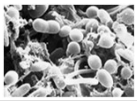
glucose → → → → → pyruvate
6C 2x 3C

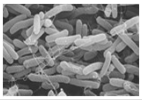
  - most ancient form of energy capture
    - starting point for all cellular respiration
  - inefficient
    - generate only 2 ATP for every 1 glucose
  - in cytosol
    - why does that make evolutionary sense?

Evolutionary perspective

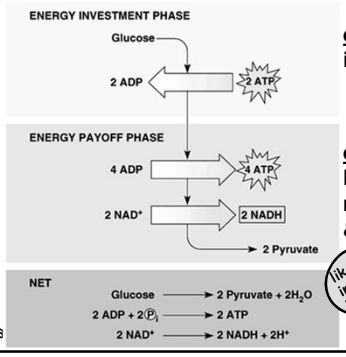


- Prokaryotes
  - first cells had no organelles
- Anaerobic atmosphere
  - life on Earth first evolved without free oxygen (O_2) in atmosphere
  - energy had to be captured from organic molecules in absence of O_2
- Prokaryotes that evolved glycolysis are ancestors of all modern life
  - ALL cells still utilize glycolysis





Glycolysis summary

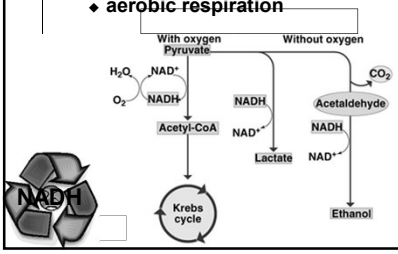


endergonic
invest some ATP

exergonic
harvest a little more ATP
& a little NADH

How is NADH recycled to NAD^+?

- Another molecule must accept H from NADH
  - aerobic respiration
    - ethanol fermentation
    - lactic acid fermentation
  - aerobic respiration



Anaerobic ethanol fermentation

- Bacteria, yeast

pyruvate → ethanol + CO_2
3C → 2C + 1C
NADH → NAD^+

  - beer, wine, bread
  - at ~12% ethanol, kills yeast

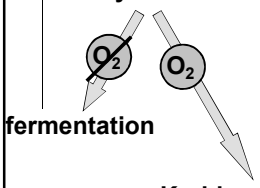
- Animals, some fungi

pyruvate → lactic acid
3C → 3C
NADH → NAD^+

  - cheese, yogurt, anaerobic exercise (no O_2)

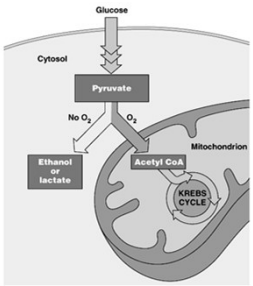
Pyruvate is a branching point

Pyruvate

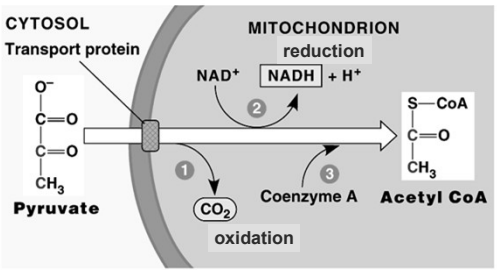


fermentation

Kreb's cycle
mitochondria

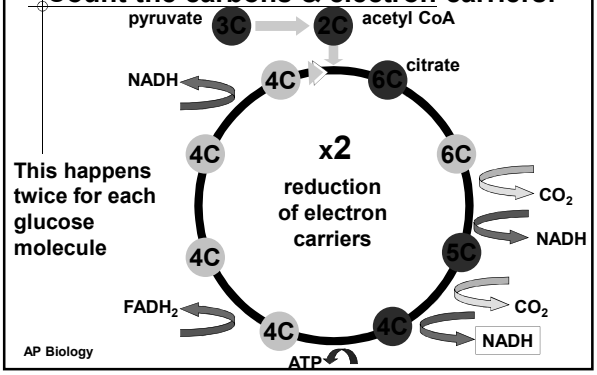


Pyruvate oxidized to Acetyl CoA



Yield = 2C sugar + CO_2 + NADH

Count the carbons & electron carriers!



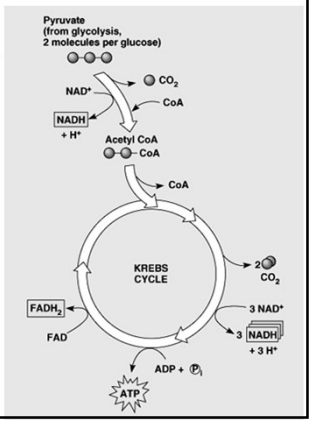
This happens twice for each glucose molecule

NADH & $FADH_2$

- Krebs cycle produces:
  - 8 NADH
  - 2 $FADH_2$
  - 2 ATP

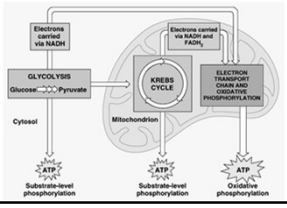
CO_2

Let's go to ETC…



So why the Krebs cycle?

- If the yield is only 2 ATP, then why?
  - value of NADH & $FADH_2$
    - electron carriers
    - reduced molecules store energy!
    - to be used in the Electron Transport Chain



ATP accounting so far…

- Glycolysis → 2 ATP
- Kreb's cycle → 2 ATP

- Life takes a lot of energy to run, need to extract more energy than 4 ATP!

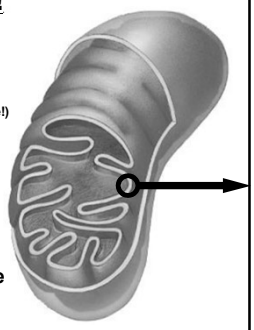
Why stop here…

Last stop and most important!

- Electron Transport Chain
  - series of molecules built into inner mitochondrial membrane
    - mostly <u>transport (integral) proteins</u>
  - transport of electrons down ETC linked to ATP synthesis
  - yields ~34 ATP from 1 glucose!
  - only in presence of O_2 (aerobic)

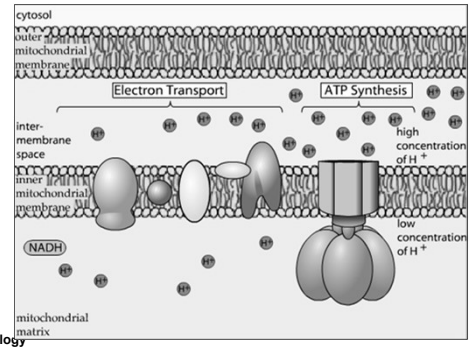
Don't forget the Mito!

- Double membrane
  - outer membrane
  - inner membrane (ETC here!)
    - highly folded cristae*
    - fluid-filled space between membranes = intermembrane space
  - Matrix (Kreb's here!)
    - central fluid-filled space



* form fits function!

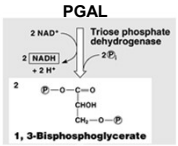
Electron Transport Chain



Remember the NADH?

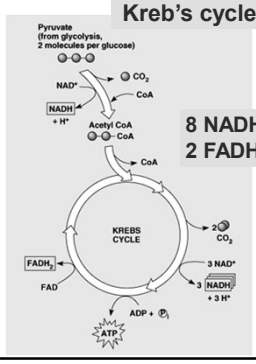
Glycolysis

PGAL



2 NADH

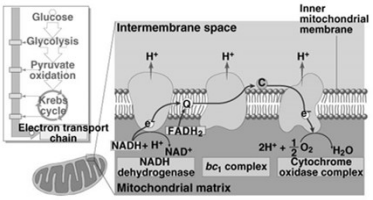
Kreb's cycle



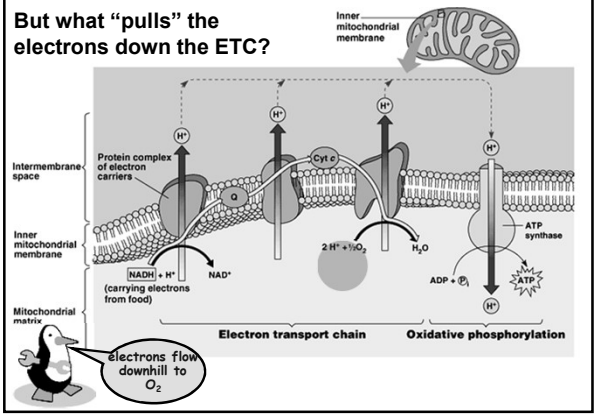
8 NADH
2 $FADH_2$

Electron Transport Chain or Chemiosmosis

- **NADH passes electrons to ETC**
  - H cleaved off NADH & $FADH_2$
  - electrons stripped from H atoms → H^+ (H ions)
  - electrons passed from one electron carrier to next in mitochondrial membrane (ETC)
  - transport proteins in membrane pump H^+ across inner membrane to intermembrane space

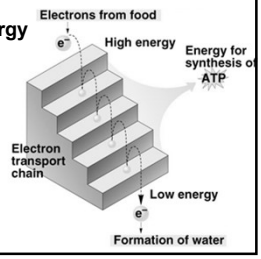


But what "pulls" the electrons down the ETC?



Electrons flow downhill

- **Electrons move in steps from carrier to carrier downhill to O_2**
  - each carrier more electronegative
  - controlled oxidation
  - controlled release of energy

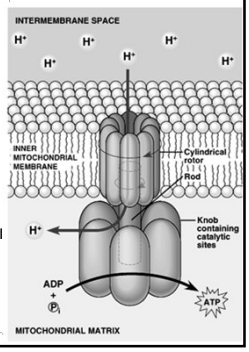


Why the build up H^+?

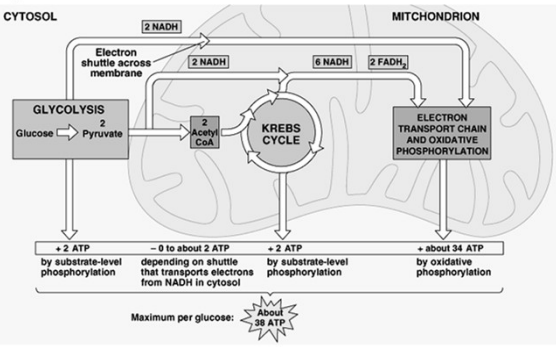
- **ATP synthase**
  - enzyme in inner membrane of mitochondria

$$ADP + P_i \rightarrow ATP$$

  - only channel permeable to H^+
  - H^+ flow down concentration gradient = provides energy for ATP synthesis
    - molecular power generator!
    - flow like water over water wheel
    - flowing H+ cause change in shape of ATP synthase enzyme
    - powers bonding of P_i to ADP
    - "proton-motive" force

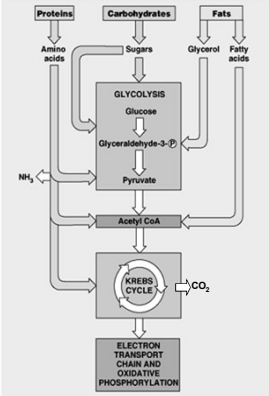


Cellular respiration



Metabolism

- Coordination of digestion & synthesis
  - by regulating enzyme
- Digestion
  - digestion of carbohydrates, fats & proteins
    - all catabolized through same pathways
    - enter at different points
  - cell extracts energy from every source



Summary of cellular respiration

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \sim 36\ ATP$$

- Where did the glucose come from?
- Where did the O_2 come from?
- Where did the CO_2 come from?
- Where did the H_2O come from?
- Where did the ATP come from?
- What else is produced that is not listed in this equation?
- Why do we breathe?

Taking it beyond…

- What is the final electron acceptor in electron transport chain?

O_2

- So what happens if O_2 unavailable?
  - ETC backs up
  - ATP production ceases
  - cells run out of energy
  - and you die!