Cellular Respiration
Stage 2 & 3

Oxidation of Pyruvate
Krebs Cycle

Glycolysis is only the start

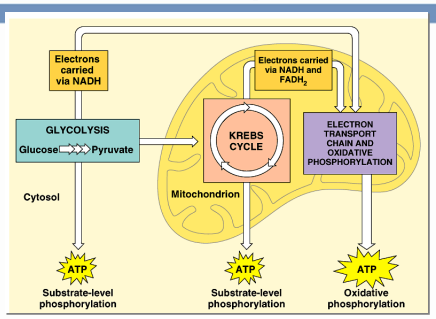
- Glycolysis

glucose → → → → → pyruvate
6C **2x 3C**

- Pyruvate has more energy to yield
  - 3 more C to strip off (to oxidize)
  - if O_2 is available, pyruvate enters mitochondria
  - enzymes of Krebs cycle complete the full oxidation of sugar to CO_2

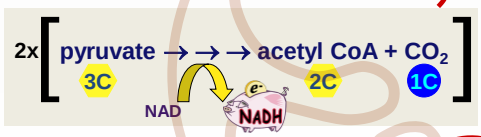
pyruvate → → → → → → CO_2
3C **1C**

Cellular respiration



Oxidation of pyruvate

- Pyruvate enters mitochondrial matrix

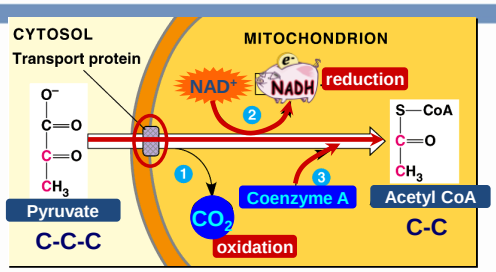


- 3 step oxidation process
- releases 2 CO_2 (count the carbons!)
- reduces 2 NAD → 2 NADH (moves e^-)
- produces 2 acetyl CoA

Where does the CO_2 go? Exhale!

- Acetyl CoA enters Krebs cycle

Pyruvate oxidized to Acetyl CoA



2 x [Yield = 2C sugar + NADH + CO_2]

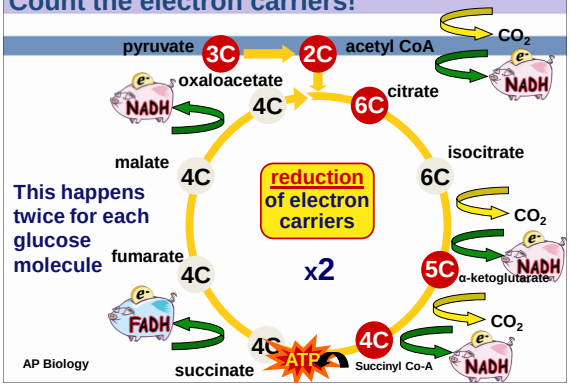
Krebs cycle

1937 | 1953

Hans Krebs
1900-1981

- aka Citric Acid Cycle
  - in mitochondrial matrix
  - 8 step pathway
    - each catalyzed by specific enzyme
    - step-wise catabolism of 6C citrate molecule
- Evolved later than glycolysis
  - does that make evolutionary sense?
    - bacteria →3.5 billion years ago (glycolysis)
    - free O_2 →2.7 billion years ago
    - eukaryotes →1.5 billion years ago (aerobic respiration = organelles → mitochondria)

Count the electron carriers!



AP Biology

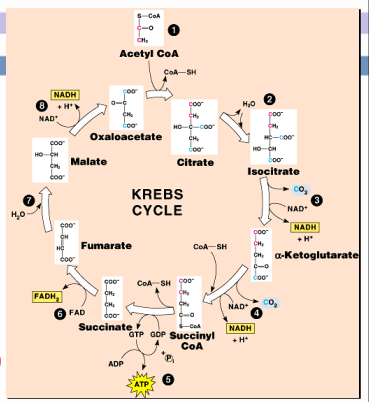
So we fully oxidized glucose

$C_6H_{12}O_6$

↓

CO_2

& ended up with 4 ATP!

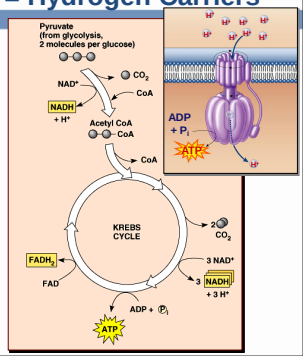


What's the point?

AP Biology

Electron Carriers = Hydrogen Carriers

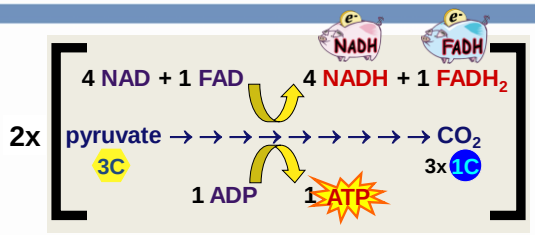
- Krebs cycle produces large quantities of electron carriers
  - NADH
  - $FADH_2$
  - go to Electron Transport Chain!



What's so important about electron carriers?

AP Biology

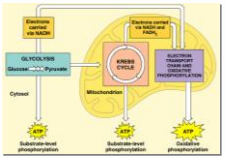
Energy accounting of Krebs cycle

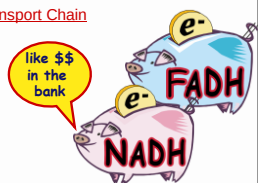


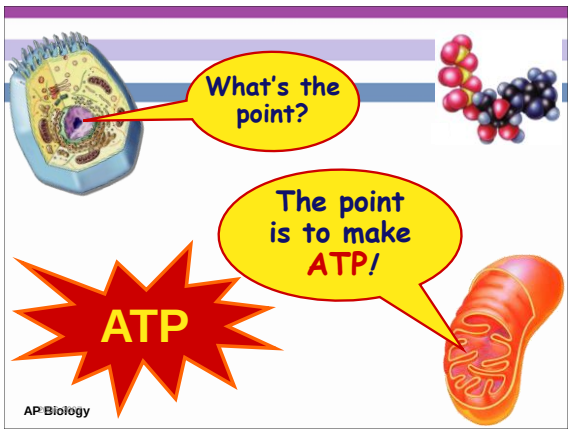
Net gain = 2 ATP
= 8 NADH + 2 $FADH_2$

Value of Krebs cycle?

- If the yield is only 2 ATP then how was the Krebs cycle an adaptation?
  - value of NADH & $FADH_2$
    - electron carriers & H carriers
      - reduced molecules move electrons
      - reduced molecules move H^+ ions
    - to be used in the Electron Transport Chain







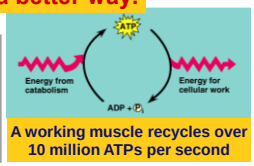
Cellular Respiration
Stage 4

Electron Transport Chain
Chemiosmosis

ATP accounting so far…

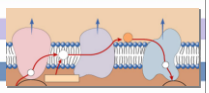
- Glycolysis → 2 ATP
- Kreb's cycle → 2 ATP
- Life takes a lot of energy to run, need to extract more energy than 4 ATP!

There's got to be a better way!



A working muscle recycles over 10 million ATPs per second

There *is* a better way!

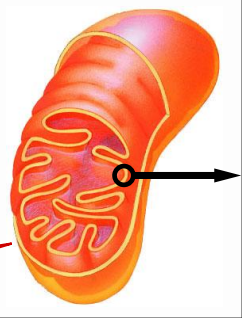


- Electron Transport Chain
  - series of proteins built into inner mitochondrial membrane
    - along cristae
    - transport proteins & enzymes
  - transport of electrons down ETC linked to pumping of H^+ to create H^+ gradient
  - yields ~36 ATP from 1 glucose!
  - only in presence of O_2 (aerobic respiration)

O_2

Mitochondria

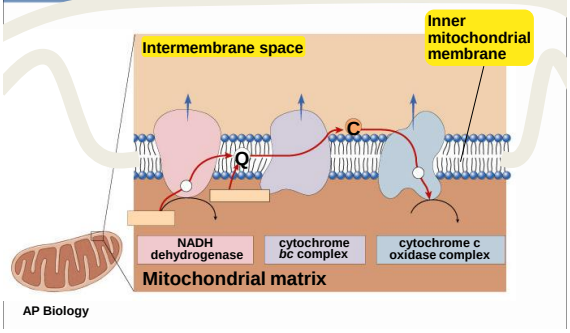
- Double membrane
  - outer membrane
  - inner membrane
    - highly folded cristae
    - enzymes & transport proteins
  - intermembrane space
    - fluid-filled space between membranes



Oooooh! Form fits function!

AP Biology

Electron Transport Chain



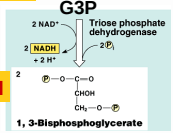
AP Biology

Remember the Electron Carriers?

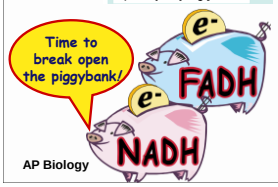
Glycolysis

glucose

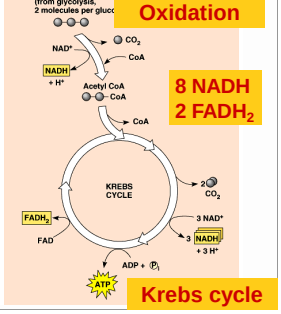
G3P



2 NADH



Pyruvate Oxidation



8 NADH
2 $FADH_2$

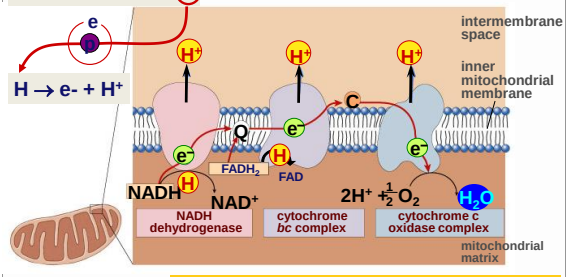
Krebs cycle

AP Biology

Electron Transport Chain

NADH → NAD⁺ + H

Building proton gradient!

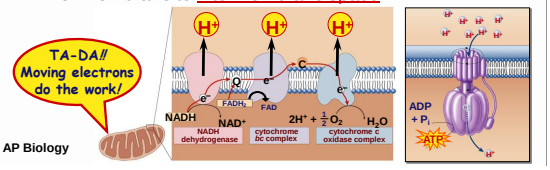


AP Biology

What powers the proton (H⁺) pumps?…

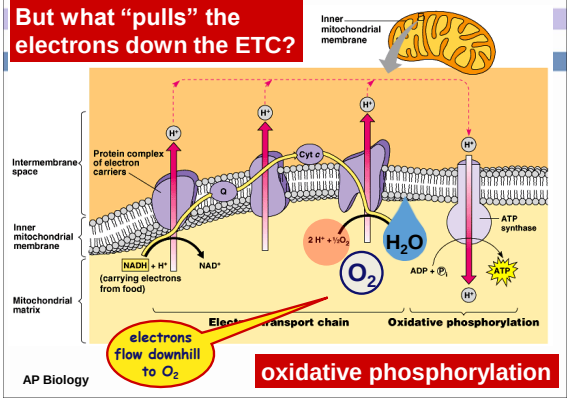
Stripping H from Electron Carriers

- Electron carriers pass electrons & H⁺ to ETC
  - H cleaved off NADH & $FADH_2$
  - electrons stripped from H atoms → H⁺ (protons)
    - electrons passed from one electron carrier to next in mitochondrial membrane (ETC), flowing electrons = energy to do work
  - transport proteins in membrane pump H⁺ (protons) across inner membrane to intermembrane space



AP Biology

But what "pulls" the electrons down the ETC?



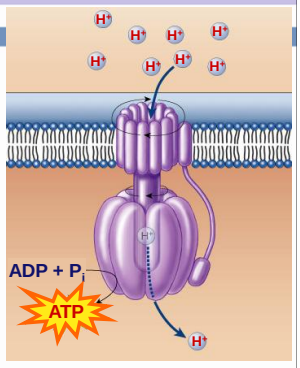
AP Biology

oxidative phosphorylation

We did it!

- Set up a H^+ gradient
- Allow the protons to flow through ATP synthase
- Synthesizes ATP

$ADP + P_i \rightarrow ATP$

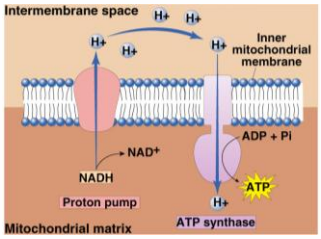


AP Biology

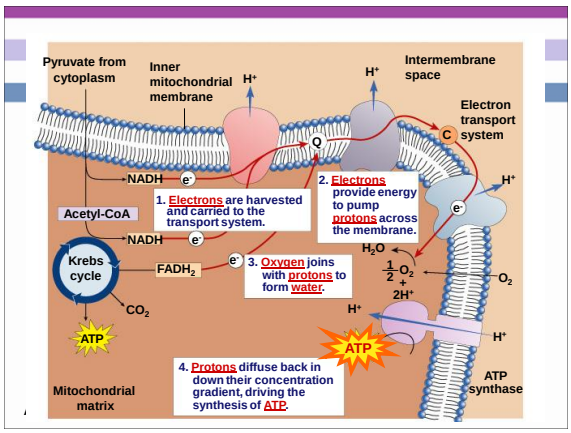
Chemiosmosis

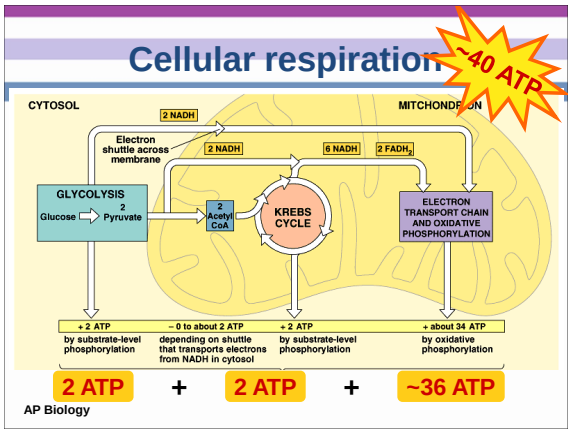
- The diffusion of ions across a membrane
  - build up of proton gradient just so H+ could flow through ATP synthase enzyme to build ATP

Chemiosmosis links the Electron Transport Chain to ATP synthesis



AP Biology




Cellular respiration
~40 ATP
CYTOSOL
MITOCHONDRION
2 NADH
Electron shuttle across membrane
2 NADH
6 NADH
2 FADH2
GLYCOLYSIS
Glucose
2 Pyruvate
2 Acetyl CoA
KREBS CYCLE
ELECTRON TRANSPORT CHAIN AND OXIDATIVE PHOSPHORYLATION
+ 2 ATP
by substrate-level phosphorylation
– 0 to about 2 ATP
depending on shuttle that transports electrons from NADH in cytosol
+ 2 ATP
by substrate-level phosphorylation
+ about 34 ATP
by oxidative phosphorylation
2 ATP + 2 ATP + ~36 ATP
AP Biology