SACRAMENTO STATE
Leadership begins here.

Chapter 5 Metabolism: *Aerobic Respiration*

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Office Hours: Mondays & Wednesdays, 8:30-10:00 AM

Some figures taken from Krogh Biology: A Guide to the Natural World

Bacterial Metabolism: 3 pathways to extract energy from glucose

- Glycolysis, followed by either
- Fermentation
  --oxidize NADH, usually without producing ATP
  --does NOT use oxygen
  or
- Aerobic Respiration
  (Krebs cycle, electron transport, oxidative phosphorylation)

To *respire aerobically*, a bacterium needs:

- Oxygen
- A cytochrome system
  - Indirectly tested for with ***catalase test***
- (For facultative anaerobes that *can* ferment), a low concentration (<0.1%) of a fermentable sugar
  - If the concentration is higher, the organism will ferment it even in the presence of O_2 (TSI test!!!) because it takes fewer enzymes/fewer reactions
  - If the bacteria CANNOT ferment the sugar, they will use it aerobically at ANY concentration, high or low

And of course, all relevant enzymes for the various biochemical pathways.

Aerobic Respiration: steps

- **Production of acetyl-CoA** from pyruvate
- **Krebs Cycle**: also called
  - Tricarboxylic acid cycle
  - TCA cycle
  - Citric acid cycle
- **Electron Transport**
  - Redox reactions with energy transfer
- **Oxidative phosphorylation**
  - Formation of ATP from ADP + Pi

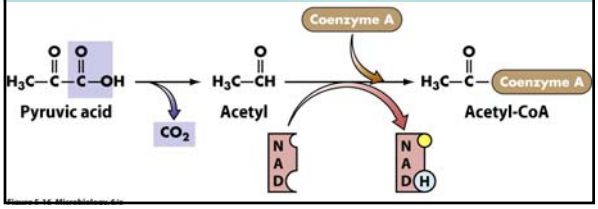
Key points: ★

- Done **INSTEAD** of fermentation
- Pyruvic acid/pyruvate is the **starting material**
- NADH is **oxidized** to NAD+ (in the end)
- Loads of **ATP** is produced
- **Oxygen** is the terminal electron acceptor, reduced to water

Acetyl-CoA

- Pyruvate is *decarboxylated* into a 2-carbon unit (with release of **CO_2**)
- Product is oxidized (NADH produced) and bound to **Coenzyme A** to make the starting product for TCA cycle,

★ **Acetyl-CoA**



★ Coenzyme A

Coenzyme A is *not* a protein

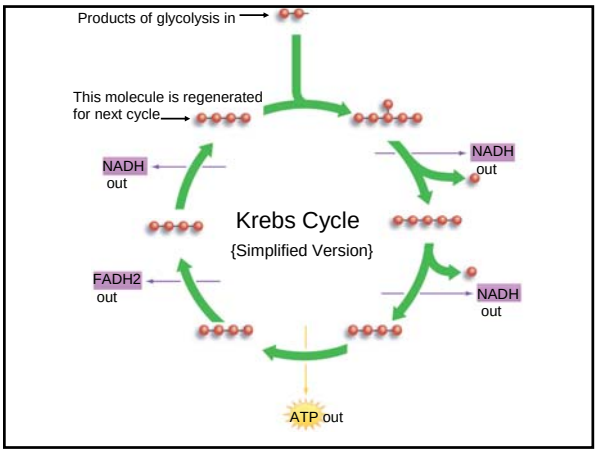
It is basically ADP with the vitamin **pantothenic acid** bound to it

It functions in multiple biochemical pathways as an "activated" (high energy) *carrier* of acetyl (2 carbon) groups (**acetyl CoA**)

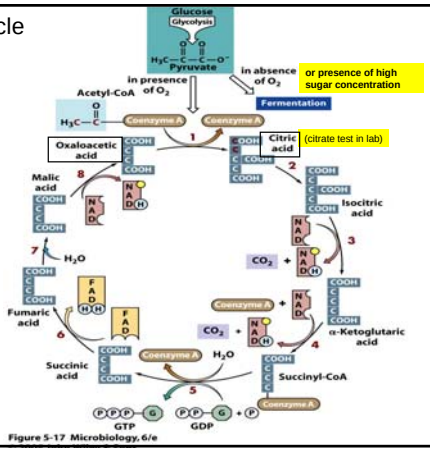
Pyruvate is converted into an "activated" Acetyl-CoA molecule for oxidation through the Krebs cycle

Krebs Cycle: What happens

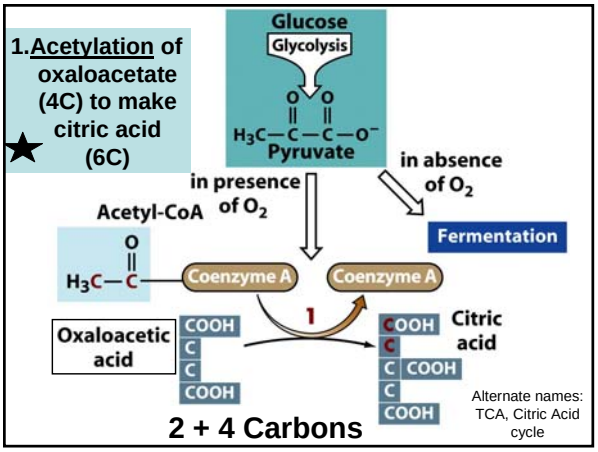
1. Those 2 **Carbons** in the acetyl group (where did they come from originally?) will be **oxidized** to CO_2
2. **Electron carriers** (NAD+ and FAD) will be **reduced** to NADH and $FADH_2$
3. **Substrate level phosphorylation**
4. **Regeneration of critical cycle component oxaloacetate**



Krebs Cycle



1. Acetylation of oxaloacetate (4C) to make citric acid (6C) ★

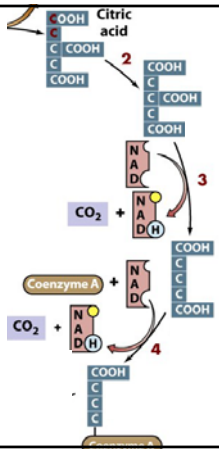


2 + 4 Carbons

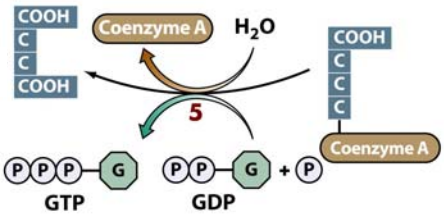
Starting with citric acid:

2. **Isomerize** ★
3. **Redox** ★
4. **Redox** ★

where "Redox" is
- **oxidation of one carbon to CO_2 (released)**
- **Reduction of NAD+ to NADH**



5. Substrate level phosphorylation
- The energy from hydrolyzing the bond with CoA is used to make GTP from GDP + P_i
- This is equivalent to making one ATP from ADP

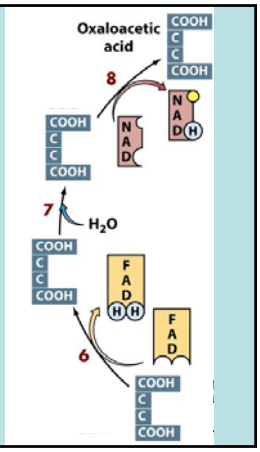


The carbons derived from glucose are GONE.

These reactions **regenerate** the crucial starting material **oxaloacetate**, allowing another ***cycle*** to begin.

Additional energy (reducing potential) is harvested by redox reactions:

6. FAD to $FADH_2$
8. NAD+ to NADH



Energy extracted *after* glycolysis

Substrate-level phosphorylation:

Krebs 1 GTP

Reducing Power:

Acetyl-CoA Production 1 NADH

Krebs 3 NADH

1 $FADH_2$

Per glucose molecule:

= 2 GTP

= 8 NADH

= 2 $FADH_2$

Where does it happen?

Aerobic Respiration & the endosymbiotic theory

All cells:

Glycolysis	Cytoplasm

Bacteria:

Krebs	Cytoplasm
ETC	Cell membrane

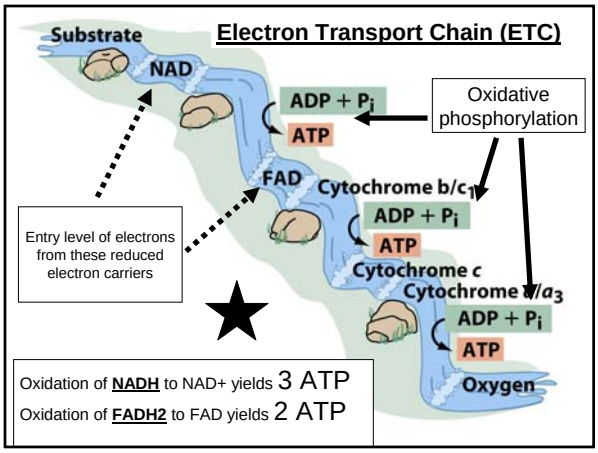
Eukaryotes:

Krebs	Mitochondrial matrix
ETC	Inner mitochondrial membrane

Electron transport & Oxidative Phosphorylation

Goal: Extract *useful* energy (ATP) by oxidizing reduced electron carriers

- Energy-carrying electrons of NADH & $FADH_2$ are passed through a series of electron carriers
- At each passage, some energy is released
- At **three** points in the chain of electrons, enough energy is released to power production of ATP from ADP + P_i
- Last electron acceptor in the chain: Oxygen



Oxidation of **NADH** to NAD+ yields 3 ATP

Oxidation of **FADH2** to FAD yields 2 ATP

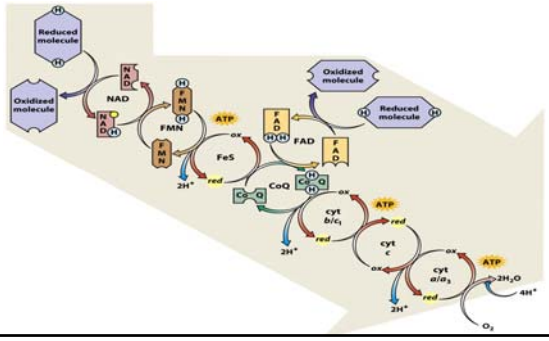
Carriers of the Electron Transport Chain

Each species has a different set of specific carrier molecules but always including the following groups:

1. Flavin mononucleotides (derivative of vitamin riboflavin)
2. Iron sulfide (FeS) centers
3. Coenzyme Q (actually a lipid)
4. Cytochromes (proteins with iron-porphyrin groups like heme)
   - Catalase test correlates with presence of cytochromes
   - Oxidase test detects a specific one, cytochrome c

This figure is NOT helpful except to illustrate this point:

The ETC is a series of linked redox reactions, with multiple energy drops (some captured to make ATP), ending in oxygen being reduced to water



About those energy drops…

Where does the energy go?

It is *not* used to make ATP directly

(that would be substrate-level phosphorylation)

•Molecules of the ETC are in the cell membrane of bacteria

•The energy released by electron transfers is used to pump protons across the membrane (out of the cell) by active transport

This generates a proton (hydrogen ion, H+) gradient

Proton Motive Force

- Energy is stored in the proton gradient
  - Higher [H+] outside than inside: ***concentration*** gradient
  - Outside of membrane is + charged relative to inside: ***electrical*** gradient

Collectively, this generates a ***proton motive force***

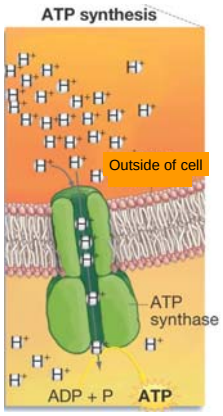
Chemiosmosis

- The energy stored in the proton gradient is used to make ATP in a process called **chemiosmosis**
- Protons are allowed *back* into the cell through **ATP synthase** complex (a transmembrane protein channel)
- Energy released from neutralizing the proton gradient is used to synthesize ATP from ADP + P_i

Chemiosmosis

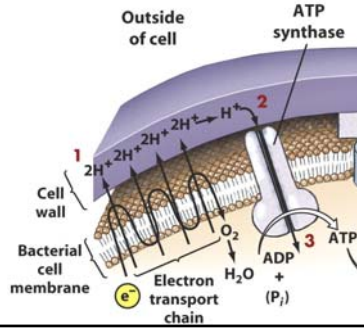
•Hydrogen ions "fall" DOWN the concentration /electrical gradient through ***ATP synthase*** protein

•Energy of "falling" is coupled to ATP production



Chemiosmosis:

1. Proton gradient is generated by ETC
2. Gradient is released by ATP synthase & coupled to ATP production



Toxins that affect aerobic respiration

★Cyanide & Azide
- Affect function of cytochromes
- Block electron transport
- Inhibits growth of catalase + bacteria
- Catalase – bacteria unaffected

★Uncoupling agents
- "uncouple" dissipation of the proton gradient from ATP synthesis
- The energy stored in the gradient is wasted
- Example: dinitrophenol

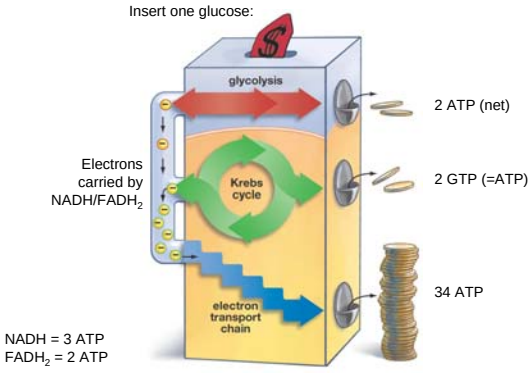


TABLE 5.2

Energy Captured in ATP Molecules from a Glucose Molecule by Anaerobic and Aerobic Metabolism in Prokaryotes

Prokaryotic Metabolic Process	Number of ATP Molecules: Anaerobic Conditions	Aerobic Conditions
Glycolysis		
Substrate level	4	4
Hydrogen to NAD	0	6
Pyruvate to Acetyl-CoA		
Hydrogen to NAD	0	6
Krebs Cycle		
Substrate level	0	2
Hydrogen to NAD	0	18
Hydrogen to FAD	0	4
Less Energy for Phosphorylation	−2	−2
Total	2	38

Table 5-2 Microbiology, 6/e

Aerobic metabolism & Growth

Bacteria using aerobic respiration for ATP production grow FASTER
(strict aerobes, facultative anaerobes in the *presence* of oxygen)

than

Bacteria relying on glycolysis & fermentation
(indifferent/aerotolerants, facultative anaerobes in the *absence* of oxygen)

★ You can see this in colony size: catalase – bacteria will generally grow more slowly / have smaller colonies than catalase + bacteria under the same aerobic conditions

TABLE 5.3

A Comparison of Metabolic Processes

	Glycolysis	Fermentation	Krebs Cycle*	Electron Transport Chain
Location	In cytoplasm	In cytoplasm	Prokaryotes: in cytoplasm Eukaryotes: in the mitochondrial matrix	Prokaryotes: in cell membrane Eukaryotes: in inner mitochondrial membranes
Oxygen Conditions	Anaerobic; oxygen is not required; does not stop, however, if oxygen is present	Without O_2, presence of oxygen will cause it to stop ✸	Aerobic	Aerobic
Starting Molecule(s)	1 glucose (6C)	Various substrate molecules go through glycolysis, yielding 2 pyruvic acid	2 pyruvic acid	6 O_2
Ending Molecules	2 pyruvic acid (3C) 2 NADH	Various, depending on which form of fermentation occurs, e.g., ethanol, lactic acid, CO_2, acetic acid	6 CO_2 8 NADH 2 FADH	6 H_2O
Amount of ATP Produced	4 ATP (net 2 ATP)	Various, depending on which form of fermentation occurs, usually 2 or 3 ATP; always far less than is produced in aerobic respiration	2 GTP (= 2 ATP)	34 ATP

*Includes the pyruvic acid → acetyl-CoA step.

Table 5-3 Microbiology, 6/e

✸ (unless a high concentration of fermentable sugar is present)

Anaerobic Respiration

★An electron transport chain is used

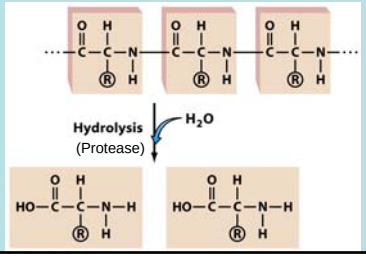
- Final electron acceptor is NOT O_2

★NO_2^-, NO_3^-, SO_4^{2-} are reduced instead

- Produce fewer ATP than aerobic respiration (but better than fermentation)

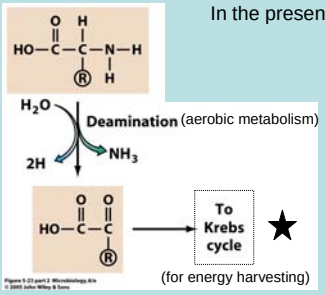
Protein catabolism

Proteins can be broken down for energy
First step:
★ **Hydrolysis into amino acids**
by ***proteases***



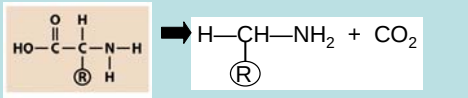
Next step for
aerobic catabolism of proteins:
★ **Deamination**

In the presence of oxygen!



For ***anaerobic*** catabolism of proteins:
★ **Decarboxylation**

In the absence of oxygen!



(to various pathways for energy harvesting)

Deamination and decarboxylation reactions are catalyzed by enzymes that are ***amino acid-specific***

Enzyme expression is ***species specific***