Environmental Microbiology

Metabolic Pathways

prepared by Prof. Bulent Icgen

Essentials of Catabolism

- Glycolysis
- Respiration and Electron Carriers
- The Proton Motive Force
- The Citric Acid Cycle
- Catabolic Diversity

Catabolic Diversity

Microorganisms demonstrate a wide range of mechanisms for generating energy

- Fermentation
- Aerobic respiration
- Anaerobic respiration
- Chemolithotrophy
- Phototrophy

Catabolic Diversity

Anaerobic Respiration

- The use of electron acceptors other than oxygen

•Examples include nitrate (NO_3^-), ferric iron (Fe^{3+}), sulfate (SO_4^{2-}), carbonate (CO_3^{2-}), certain organic compounds

- Less energy released compared to aerobic respiration
- Dependent on electron transport, generation of a proton motive force, and ATPase activity

Catabolic Diversity

Chemolithotrophy

- Uses inorganic chemicals as electron donors

•Examples include hydrogen sulfide (H_2S), hydrogen gas (H_2), ferrous iron (Fe^{2+}), ammonia (NH_3)

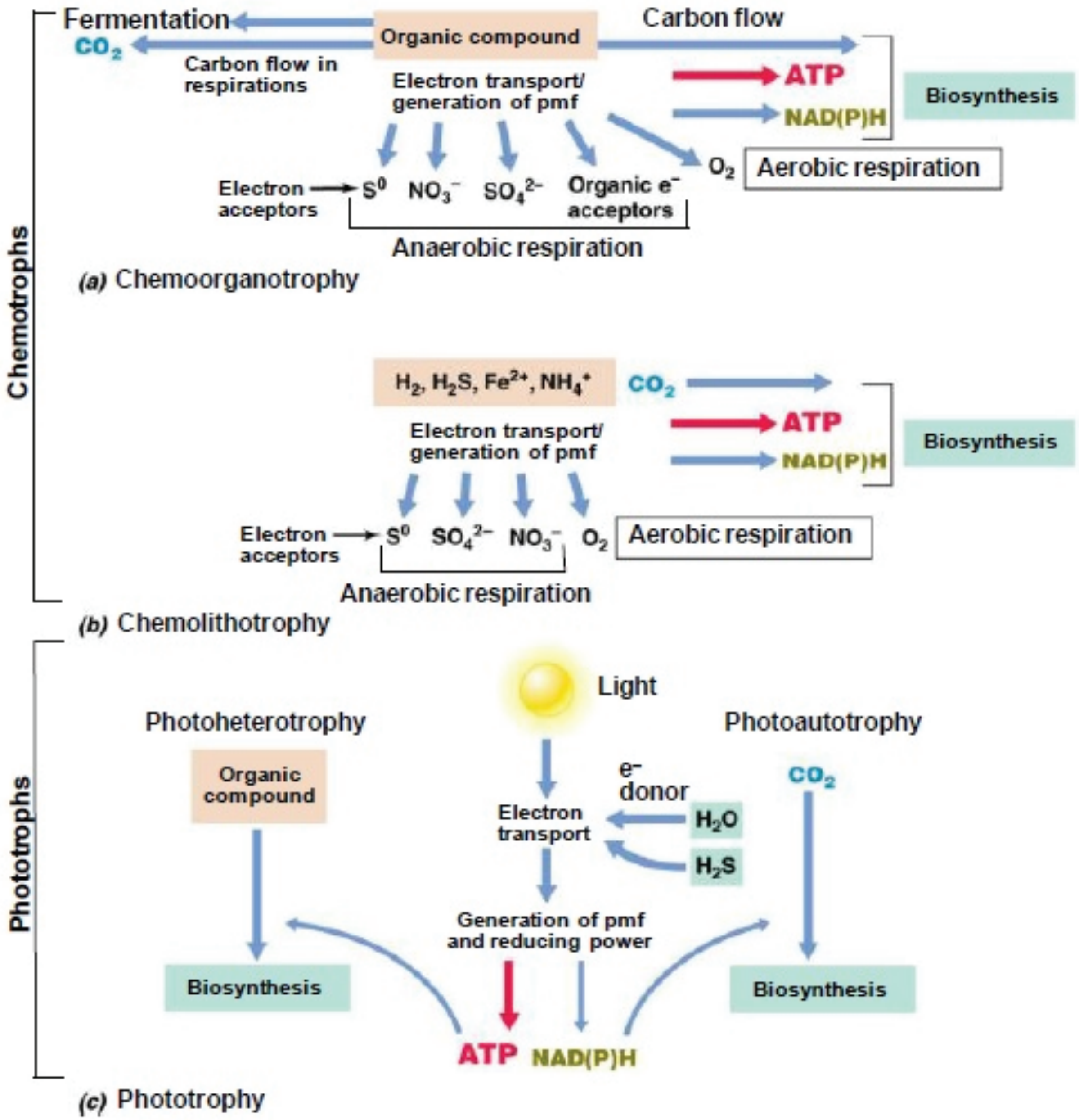
- Typically aerobic
- Begins with oxidation of inorganic electron donor
- Uses electron transport chain and proton motive force
- Autotrophic; uses CO_2 as carbon source

Catabolic Diversity

Phototrophy: uses light as energy source

- Photophosphorylation: light-mediated ATP synthesis
- Photoautotrophs: use ATP for assimilation of CO_2 for biosynthesis
- Photoheterotrophs: use ATP for assimilation of organic carbon for biosynthesis

Catabolic Diversity



Chemoorganotrophs differ from chemolithotrophs in two important ways:

1. The nature of the electron donor (organic vs. inorganic compounds, respectively) and
2. The nature of the source of cellular carbon (organic compounds vs. CO_2 respectively).

However, note the importance of electron transport driving proton motive force formation in all forms of respiration and in photosynthesis.

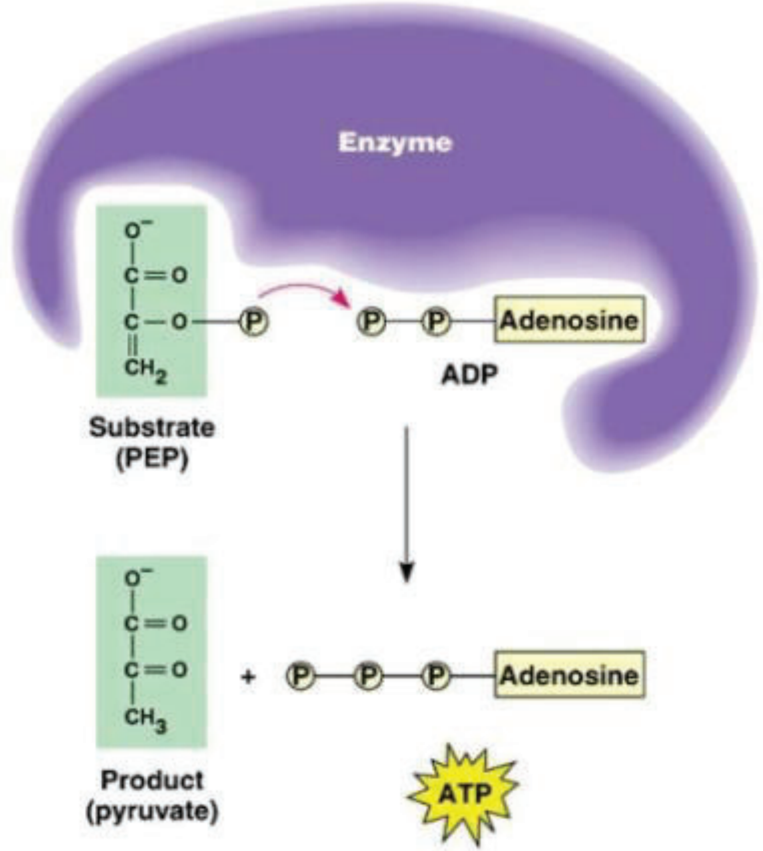
Glycolysis

- Two reaction series are linked to energy conservation in chemoorganotrophs: fermentation and respiration
- Differ in mechanism of ATP synthesis
- Fermentation: substrate-level phosphorylation; ATP directly synthesized from an energy-rich intermediate
- Respiration: oxidative phosphorylation; ATP produced from proton motive force formed by transport of electrons

ATP Synthesis = Phosphorylation

3 types of phosphorylation:

- Substrate Level Phosphorylation
  - ATP synthesis during glycolysis
- Oxidative Phosphorylation
  - ATP synthesis during electron transport chain
- Photophosphorylation
  - ATP synthesis during photosynthesis



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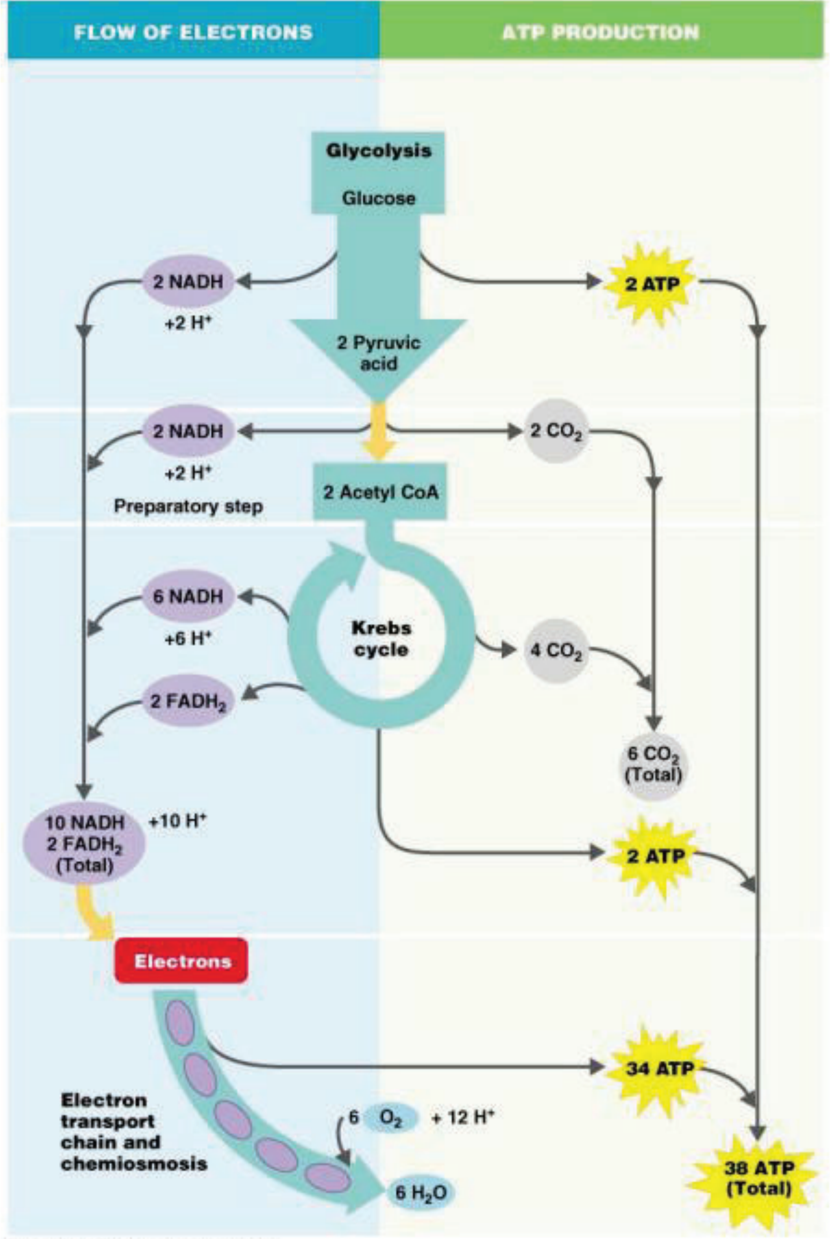
Metabolism for Energy Production

- Energy production involves a series of oxidation-reduction reactions to slowly release the energy stored in organic molecules
  - if not released in a slow stepwise process too much energy would be lost to heat and destroy the cell/organism

- Carbohydrate catabolism by microorganisms involves 2 general processes cellular respiration and/or fermentation
  - *Glycolysis* (part of cellular respiration & fermentation)
  - *Krebs cycle*
  - *Electron transport chain*



1 NADH = 3ATP 1FADH = 2ATP

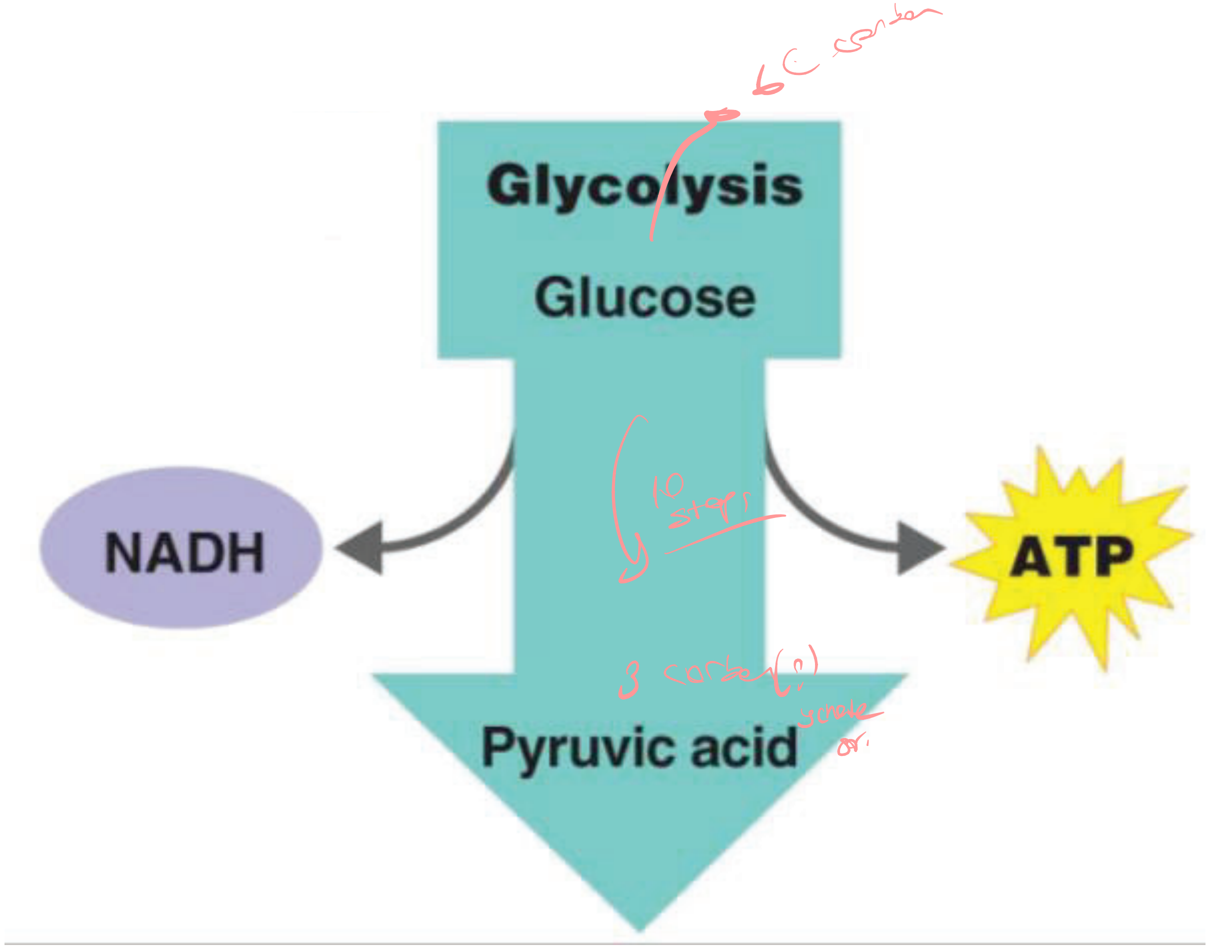
intermadiete step → very productive

creb cycle → highly production in terms of energy.

2ATP → produced substrate level.

Glycolysis (Embden-Meyerhof Pathway)

- The oxidation of glucose to pyruvic acid (aka pyruvate) produces ATP and NADH



6C carbon

10 steps

3 carbon(s)

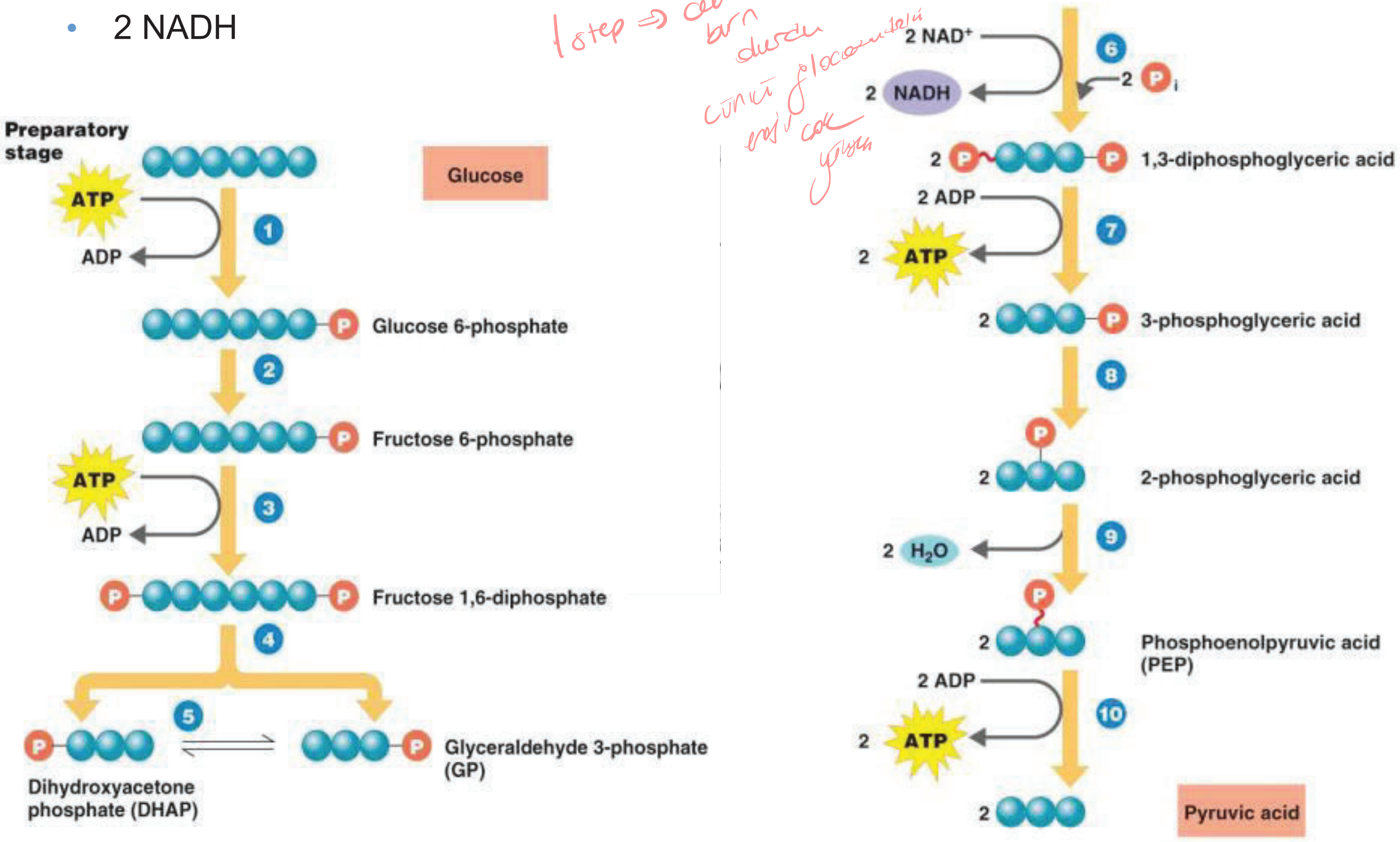
ychate

or.

Glycolysis

- Total NET production of energy in Glycolysis:
  - 2 ATP
  - 2 NADH

1 step ⇒ cell brn durdu çünkü glocozundaki enji çok yüksek



Microbial Alternatives to Glycolysis

- Pentose phosphate pathway
  - uses pentoses (5 carbon sugars) and NADPH
  - operates simultaneously with glycolysis in some bacteria
  - occurs in the cytosol
  - *Bacillus subtilus*, *E. coli*, *Leuconostoc mesenteroides* & *Enterococcus faecalis*
- Entner-Doudoroff pathway
  - an alternate pathway that catabolizes glucose to pyruvate using different enzymes than glycolysis and the pentose phosphate pathway
  - produces NADPH and ATP like glycolysis
  - gram (-) bacteria – *Pseudomonas, Rhizobium, Agrobacterium*

Krebs Cycle

- The 2 pyruvate from glycolysis are converted to 2 acetyl CoA in an intermediate reaction that generates 2 NADH
- For every 2 acetyl CoA that enter the Krebs cycle, 6 molecules of NADH, 2 FADH & 2 ATP are produced
- Many of the intermediates in the Krebs cycle also play a role in other pathways like amino acid biosynthesis
- End result of the metabolism of one molecule of glucose after glycolysis, Krebs & electron transport is 38 ATP (36 for eukaryotic organisms)

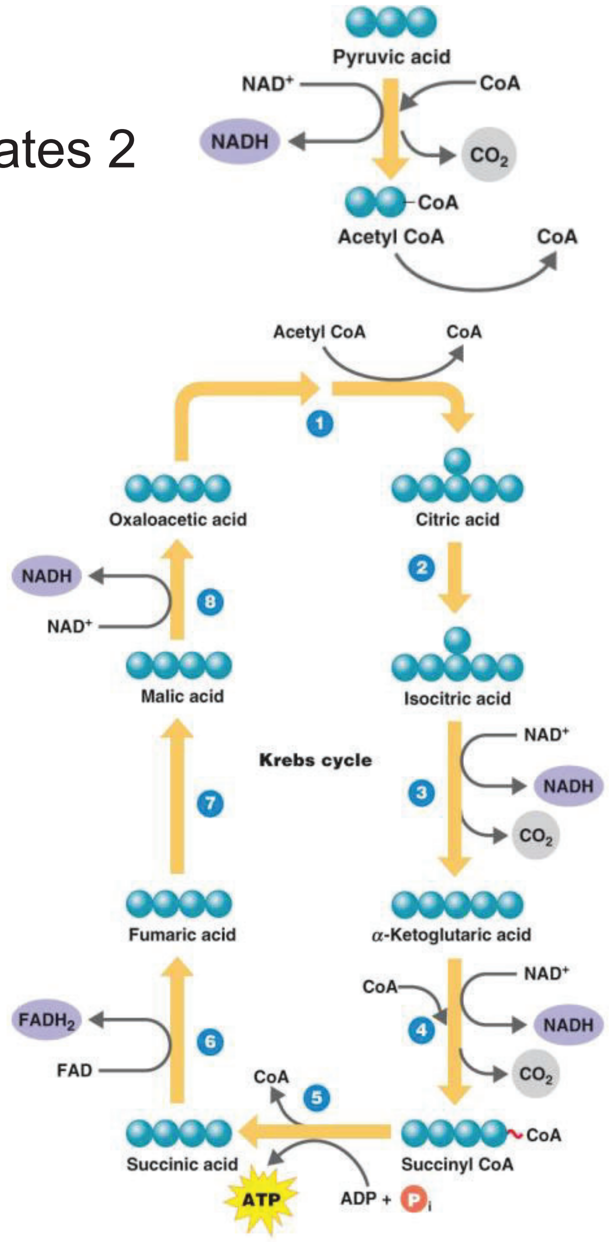
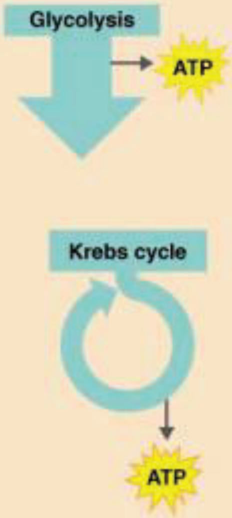
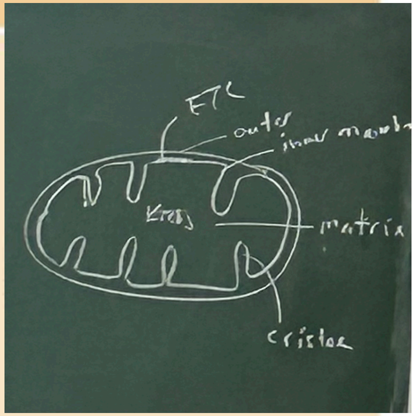


Table 5.3 ATP Yield during Prokaryotic Aerobic Respiration of One Glucose Molecule



Source	ATP Yield (Method)
Glycolysis	
1. Oxidation of glucose to pyruvic acid	2 ATP (substrate-level phosphorylation)
2. Production of 2 NADH	6 ATP (oxidative phosphorylation in electron transport chain)
Preparatory Step	
1. Formation of acetyl CoA produces 2 NADH	6 ATP (oxidative phosphorylation in electron transport chain)
Krebs Cycle	
1. Oxidation of succinyl CoA to succinic acid	2 GTP (equivalent of ATP; substrate-level phosphorylation)
2. Production of 6 NADH	18 ATP (oxidative phosphorylation in electron transport chain)
3. Production of 2 FADH	4 ATP (oxidative phosphorylation in electron transport chain)
	Total: 38 ATP



4 prokaryotic Eukaryotic = 38ATP

Cowing = ? Some of the energy loss from mitochondria
during the transfer.

Anaerobic Respiration

- Anaerobic Respiration: General Principles
- Nitrate Reduction and Denitrification
- Sulfate and Sulfur Reduction
- Acetogenesis
- Methanogenesis
- Proton Reduction
- Other Electron Acceptors
- Anoxic Hydrocarbon Oxidation Linked to Anaerobic Respiration

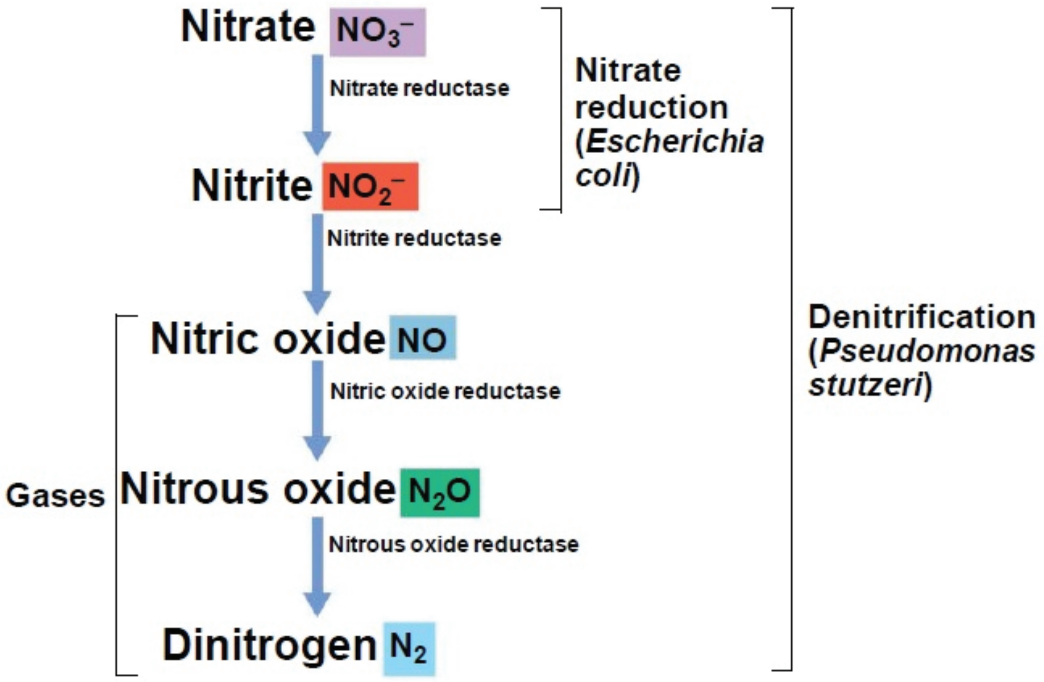
Anaerobic Respiration: General Principles

- In anaerobic respiration, electron acceptors other than O_2 are used
- Anaerobic and aerobic respiratory systems are similar
- But anaerobic respiration yields less energy than aerobic respiration
- Energy released from redox reactions can be determined by comparing reduction potentials
- In the assimilative metabolism of an inorganic compound (e.g., NO_3^-, SO_4^{2-}, CO_2) the reduced compounds are used in biosynthesis
- During anaerobic respiration, the reduction of inorganic compounds is called dissimilative metabolism because the reduced products are excreted

Nitrate Reduction and Denitrification

- Inorganic nitrogen compounds are the most common electron acceptors in anaerobic respiration
- All products of nitrate reduction (denitrification) are gaseous
- Denitrification is the main biological source of gaseous N_2
- Enzymes of the pathway are repressed by oxygen

Steps in the dissimilative reduction of nitrate



Nitrate NO_3^-

Nitrate reductase

Nitrite NO_2^-

Nitrite reductase

Nitric oxide NO

Nitric oxide reductase

Nitrous oxide N_2O

Nitrous oxide reductase

Dinitrogen N_2

Gases

Nitrate reduction (*Escherichia coli*)

Denitrification (*Pseudomonas stutzeri*)

Sulfate and Sulfur Reduction

- Inorganic sulfur compounds can be used as electron acceptors in anaerobic respiration
- Reduction of SO_4^{2-} to H_2S proceeds through several intermediates and requires activation of sulfate by ATP.

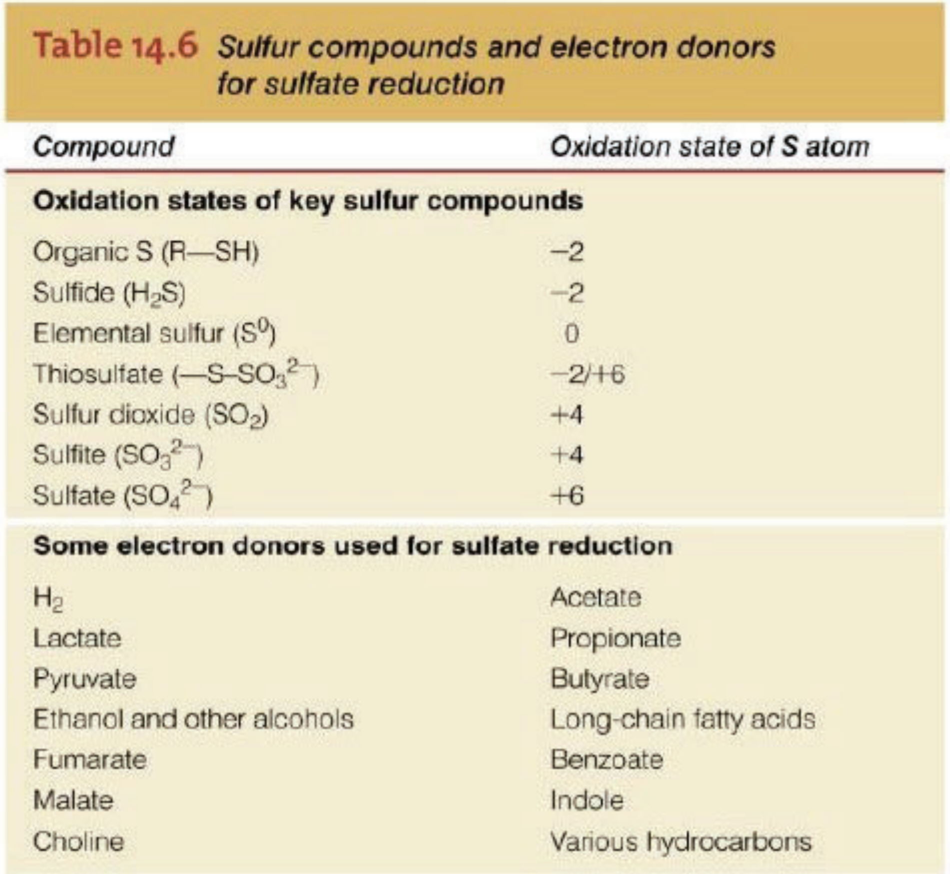


Table 14.6 ***Sulfur compounds and electron donors for sulfate reduction***

Compound	*Oxidation state of S atom*
Oxidation states of key sulfur compounds	
Organic S (R—SH)	−2
Sulfide (H_2S)	−2
Elemental sulfur (S^0)	0
Thiosulfate ($—S\text{–}SO_3^{2-}$)	−2/+6
Sulfur dioxide (SO_2)	+4
Sulfite (SO_3^{2-})	+4
Sulfate (SO_4^{2-})	+6
Some electron donors used for sulfate reduction	
H_2	Acetate
Lactate	Propionate
Pyruvate	Butyrate
Ethanol and other alcohols	Long-chain fatty acids
Fumarate	Benzoate
Malate	Indole
Choline	Various hydrocarbons

Sulfate and Sulfur Reduction

- Many different compounds can serve as electron donors in sulfate reduction

Examples: H2, organic compounds, phosphite

$$4H_2 + SO_4^{2-} + H^+ \Rightarrow HS^- + 4H_2O \qquad \Delta G^{0'} = -152\ kJ$$

$$CH_3COO^- + SO_4^{2-} + 3\ H^+ \Rightarrow CO_2 + H_2S + 2H_2O \qquad \Delta G^{0'} = -57.5\ kJ$$

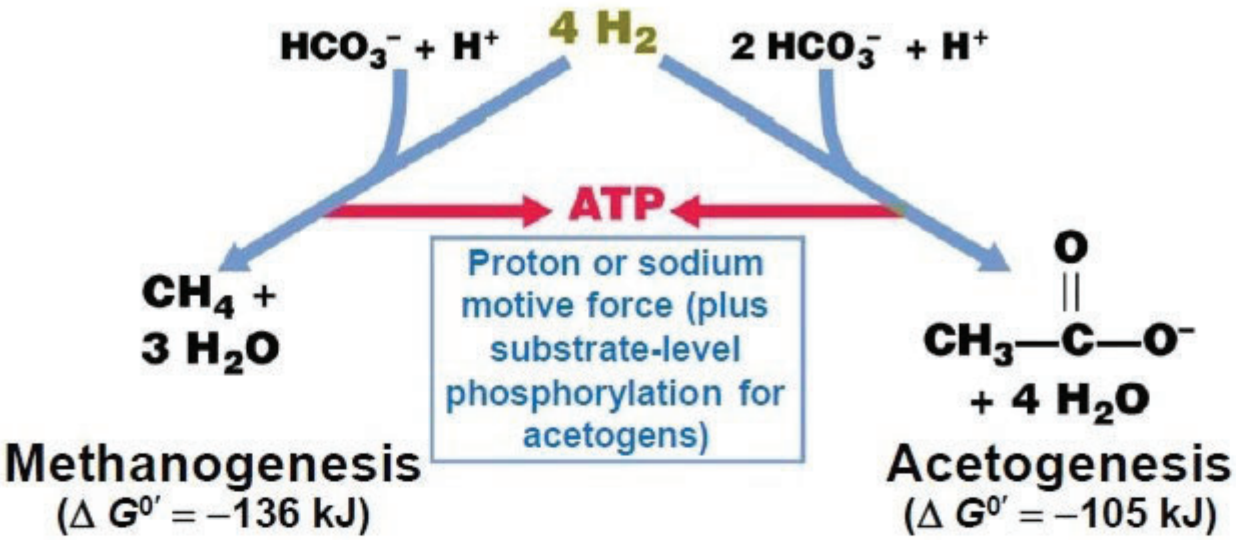
$$4HPO_3 + SO_4^{2-} + H^+ \Rightarrow 4HPO_4^{2-} + HS^- \qquad \Delta G^{0'} = -364\ kJ$$

Acetogenesis

- Acetogens and methanogens use CO_2 as an electron acceptor in anaerobic respiration
- H_2 is the major electron donor for both groups of organisms
- Acetogens carry out the reaction

$$4H_2 + H^+ + 2HCO_3^- \Longrightarrow CH3COO^- + 4H_2O \ \Delta G^{0'} = -105 \text{ kJ}$$

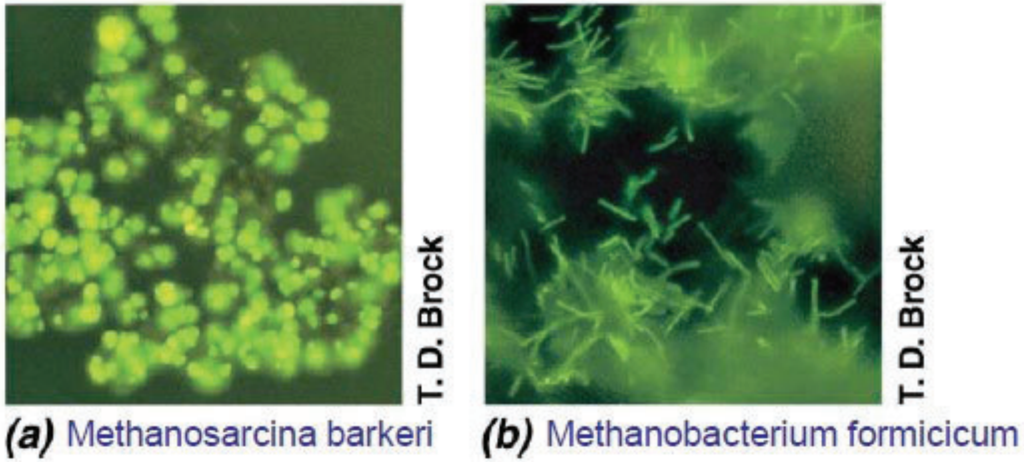
The contrasting processes of methanogenesis and acetogenesis



Methanogenesis

Biological production of methane

- Carried out by a group of strictly anaerobic
- Archaea called the methanogens
- Involves a complex series of biochemical reactions that use novel coenzymes
- The autofluorescence of coenzyme F_{420} can be used to identify methanogens microscopically



(a) Methanosarcina barkeri ***(b)*** Methanobacterium formicicum

Fluorescence due to the methanogenic coenzyme F_{420}. The organisms were made visible by excitation with blue light in a fluorescence microscope

Methanogenesis

- H_2 is the major electron donor for methanogenesis (Figure 14.20)

$$4\ H_2 + CO_2 \rightarrow CH_4 + 2\ H_2O$$

$$\Delta G^{0\prime} = -130.7\ \text{kJ/reaction}$$

- Additional electron donors exist
  - Examples: formate, CO, organic compounds

$$\boxed{\text{Acetate}^- + H^+ \longrightarrow CO_2 + CH_4\ \Delta G^{0\prime} = -37\text{kJ}}$$

$$\boxed{4CH_3OH \longrightarrow 3CH_4 + CO_2 + 2H_2O \quad \Delta G^{0\prime} = -321\text{kJ}}$$

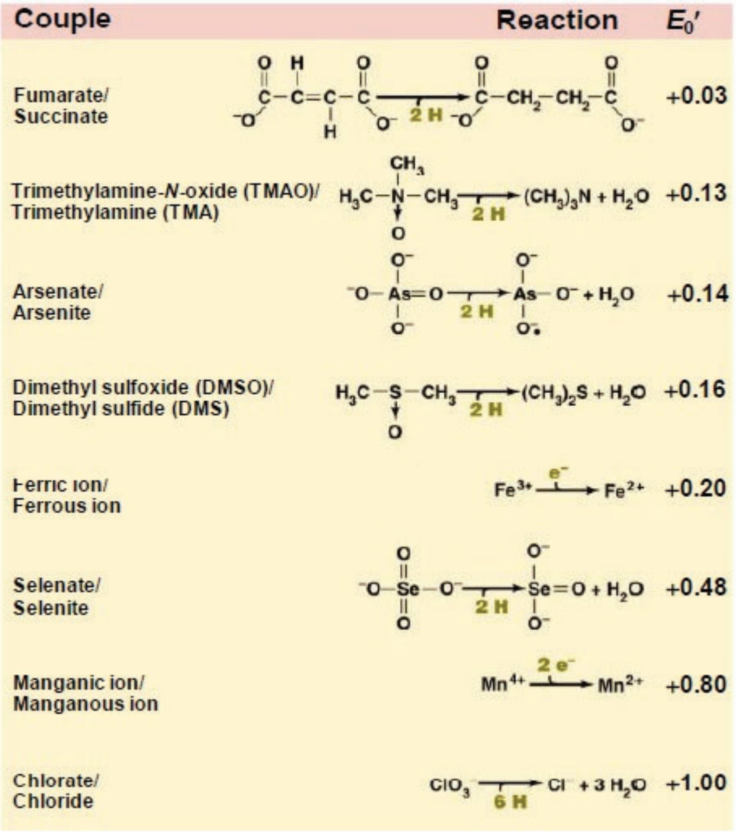
Proton Reduction

- *Pyrococcus furiosus*
  - Member of the Archaea
  - Grows optimally at 100°C on sugars and small peptides as electron donors
  - May have the simplest anaerobic respiration mechanism
  - Organism uses modified glycolysis and protons in anaerobic respiration linked to ATPase activity

Other Electron Acceptors

- Fe^{3+}, Mn^{4+}, ClO_3^-, and various organic compounds can serve as electron acceptors for bacteria
- Fe^{3+} is abundant in nature and its reduction is a major form of anaerobic respiration

Some alternative electron acceptors for anaerobic respirations



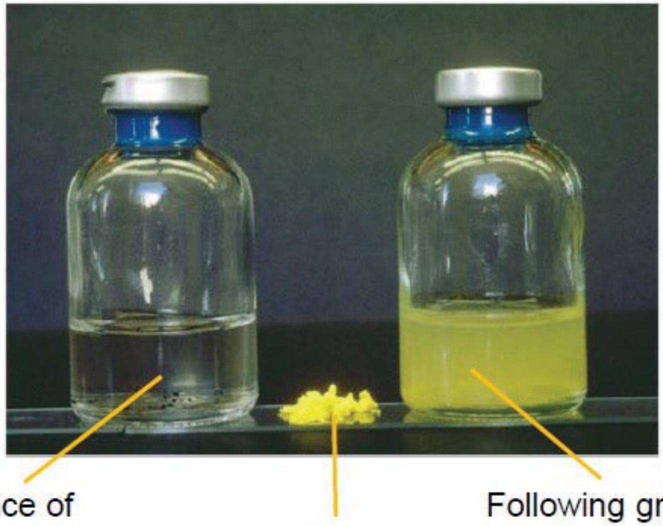
Couple	Reaction	E_0'
Fumarate/ Succinate	$^-O-C(=O)-CH=CH-C(=O)-O^- \xrightarrow{2\,H} {}^-O-C(=O)-CH_2-CH_2-C(=O)-O^-$	+0.03
Trimethylamine-*N*-oxide (TMAO)/ Trimethylamine (TMA)	$H_3C-N(CH_3)(\rightarrow O)-CH_3 \xrightarrow{2\,H} (CH_3)_3N + H_2O$	+0.13
Arsenate/ Arsenite	$^-O-As(=O)(O^-)-O^- \xrightarrow{2\,H} As(O^-)_2-O^- + H_2O$	+0.14
Dimethyl sulfoxide (DMSO)/ Dimethyl sulfide (DMS)	$H_3C-S(\rightarrow O)-CH_3 \xrightarrow{2\,H} (CH_3)_2S + H_2O$	+0.16
Ferric ion/ Ferrous ion	$Fe^{3+} \xrightarrow{e^-} Fe^{2+}$	+0.20
Selenate/ Selenite	$^-O-Se(=O)_2-O^- \xrightarrow{2\,H} (O^-)_2Se=O + H_2O$	+0.48
Manganic ion/ Manganous ion	$Mn^{4+} \xrightarrow{2\,e^-} Mn^{2+}$	+0.80
Chlorate/ Chloride	$ClO_3 \xrightarrow{6\,H} Cl^- + 3\,H_2O$	+1.00

Other Electron Acceptors

- The reduction of arsenate has been employed for cleanup of toxic wastes and groundwater
- Halogenated compounds can also serve as electron acceptors via a process called reductive dechlorination (dehalorespiration)

Biomineralization during arsenate reduction by the sulfate-reducing bacterium *Desulfotomaculum auripigmentum*

Desulfotomaculum can reduce AsO_4^{3-} to AsO_3^{3-}, along with sulfate (SO_4^{2-}) to sulfide (HS^-)



Dianne K. Newman and Stephen Tay

Appearance of culture bottle after inoculation

Synthetic sample of As_2S_3

Following growth for 2 weeks and biomineralization of arsenic trisulfide, As_2S_3

Anoxic Hydrocarbon Oxidation

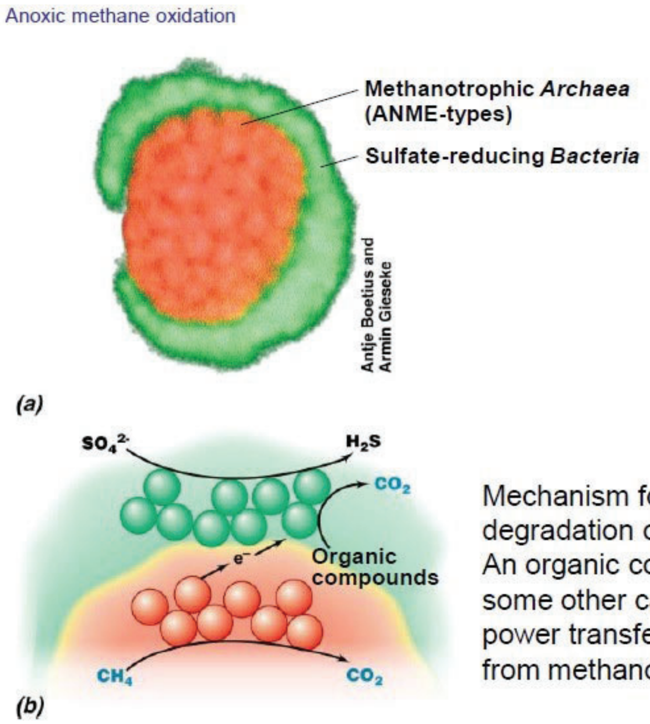
- Aliphatic and aromatic hydrocarbons and organic compounds containing only carbon and hydrogen can be oxidized anaerobically
- The first step in degradation is the addition of oxygen to the molecule through the incorporation of fumarate
- Hydrocarbons are oxidized to intermediates that can be catabolized via the citric acid cycle
- Aliphatic hydrocarbons are straight-chain saturated or unsaturated compounds
- Many of them are substrates for denitrifying and sulfate-reducing bacteria
- Aromatic hydrocarbons are catabolized by ring reduction and cleavage
- Can be degraded by some denitrifying, ferric iron-reducing, and sulfate-reducing bacteria

Anoxic Hydrocarbon Oxidation

Methane

- The simplest hydrocarbon
- Can be oxidized under anoxic conditions by a consortia containing sulfate-reducing bacteria and methanotrophic archaea

$$CH_4 + SO_4^{2-} + H^+ \longrightarrow CO_2 + HS^- + 2H_2O \quad \Delta G^{0\prime} = -18\ \text{kJ}$$



Mechanism for cooperative degradation of CH_4. An organic compound or some other carrier of reducing power transfers electrons from methanotroph to SRB.

Fermentation Definitions

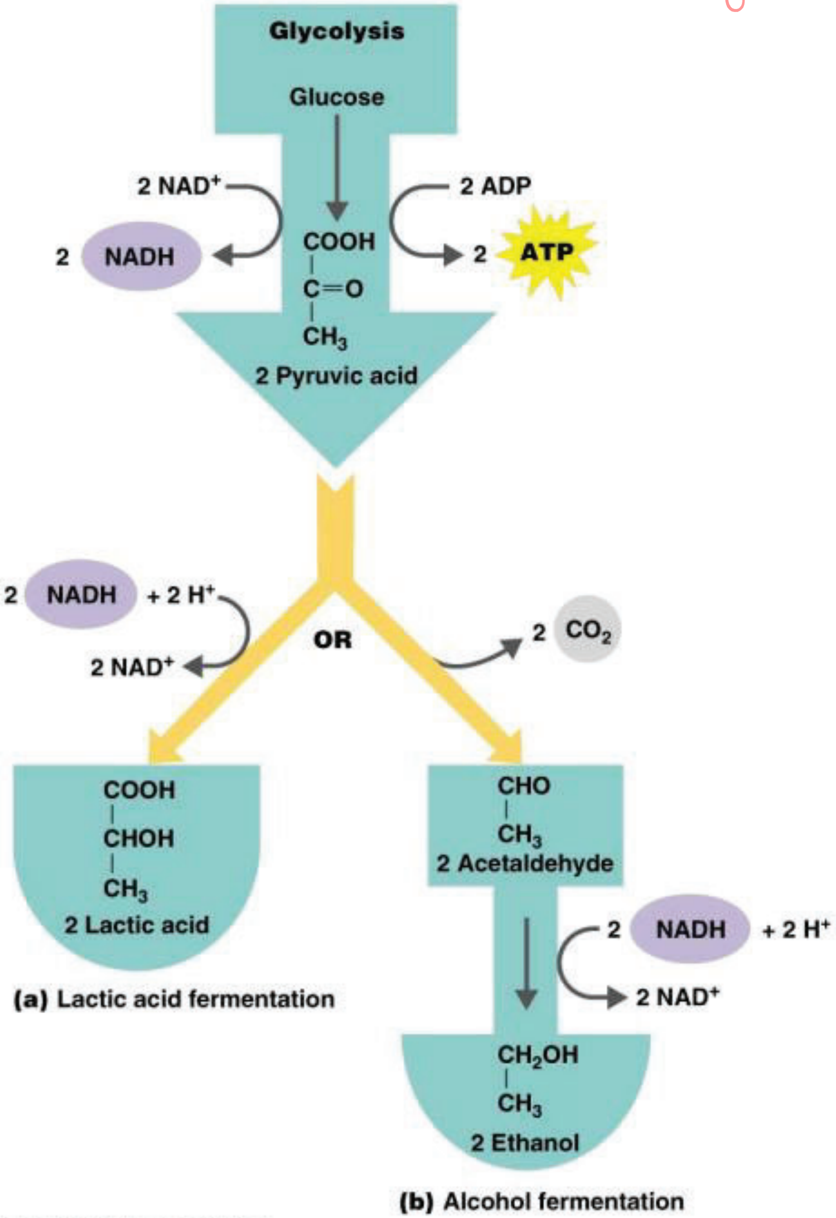
- Any spoilage of food by microorganisms (general use)
- Any process that produces alcoholic beverages or acidic dairy products (general use)
- Any large-scale microbial process occurring with or without air (common definition used in industry)
- Scientific definition:
  - releases energy from oxidation of organic molecules
  - does not require oxygen
  - does not use the Krebs cycle or ETC
  - uses an organic molecule as the final electron acceptor

fermentative bacteria

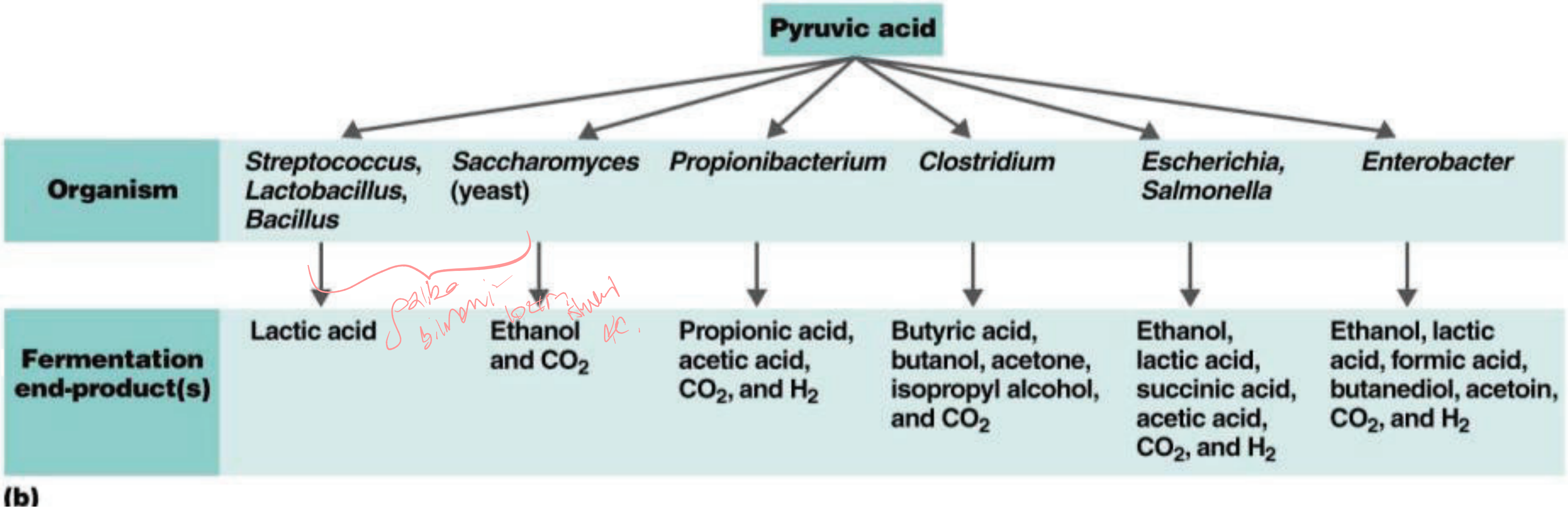
cant go through oxidative fermentation

↳ no electron chain

only 2ATP



End-Products of Fermentation



Pyruvic acid

Organism	*Streptococcus, Lactobacillus, Bacillus*	*Saccharomyces* (yeast)	*Propionibacterium*	*Clostridium*	*Escherichia, Salmonella*	*Enterobacter*
Fermentation end-product(s)	Lactic acid	Ethanol and CO_2	Propionic acid, acetic acid, CO_2, and H_2	Butyric acid, butanol, acetone, isopropyl alcohol, and CO_2	Ethanol, lactic acid, succinic acid, acetic acid, CO_2, and H_2	Ethanol, lactic acid, formic acid, butanediol, acetoin, CO_2, and H_2

palbe bilinmi lozim shuni kc.

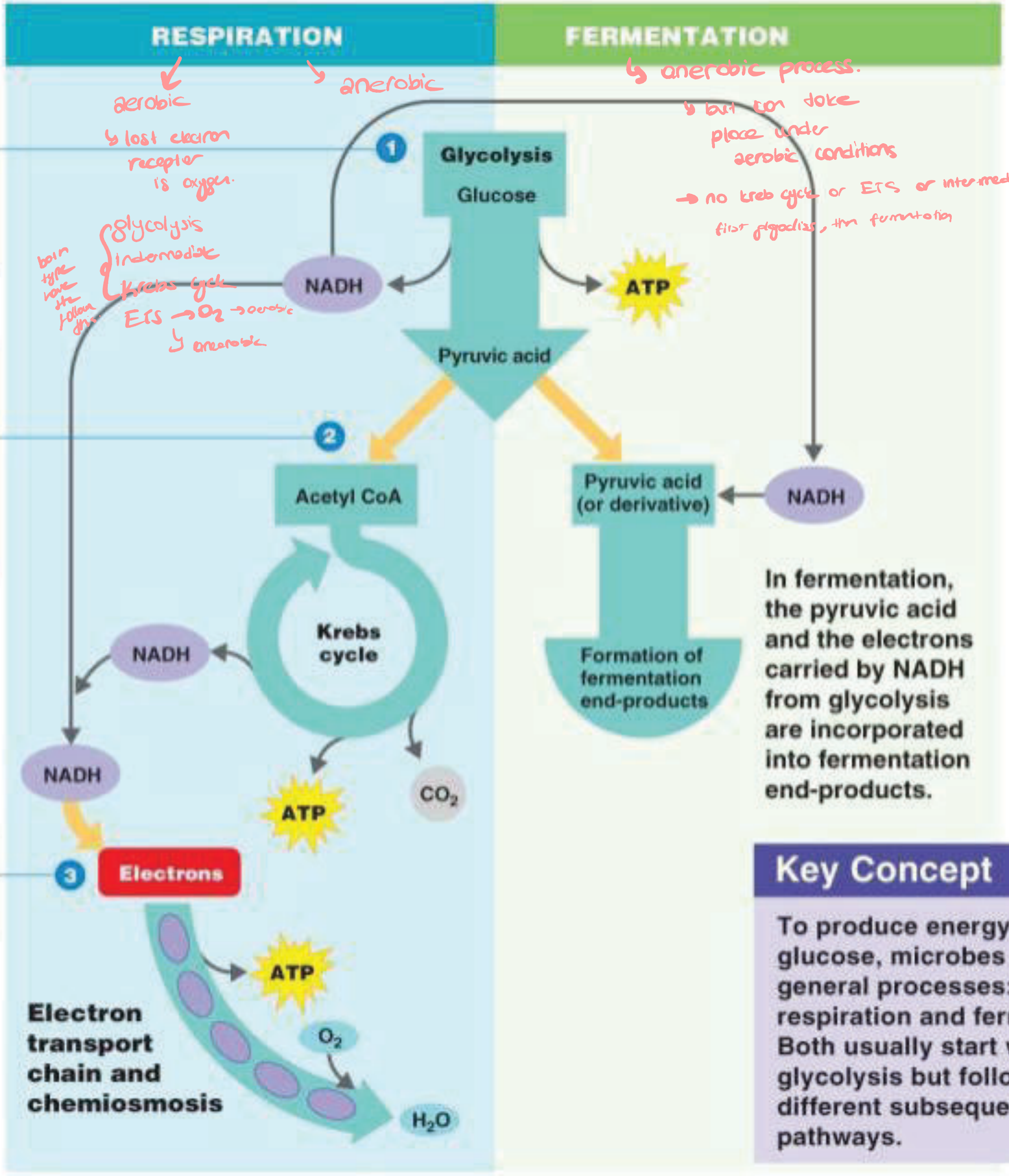
(b)

Overview of Respiration & Fermentation

① Glycolysis produces ATP and reduces NAD⁺ to NADH while oxidizing glucose to pyruvic acid. In respiration, the pyruvic acid is converted to the first reactant in the Krebs cycle.

② The Krebs cycle produces ATP and reduces NAD⁺ (and another electron carrier called $FADH_2$) while giving off CO_2. The NADH and $FADH_2$ from both processes carry electrons to the electron transport chain.

③ In the electron transport chain, the energy of the electrons is used to produce a great deal of ATP.



In fermentation, the pyruvic acid and the electrons carried by NADH from glycolysis are incorporated into fermentation end-products.

aerobic
↳ lost electron receptor is oxygen.

anerobic

both type have the follow this:
glycolysis
indermediate
Krebs cycle
ETS → O_2 → aerobic
↳ anerobic

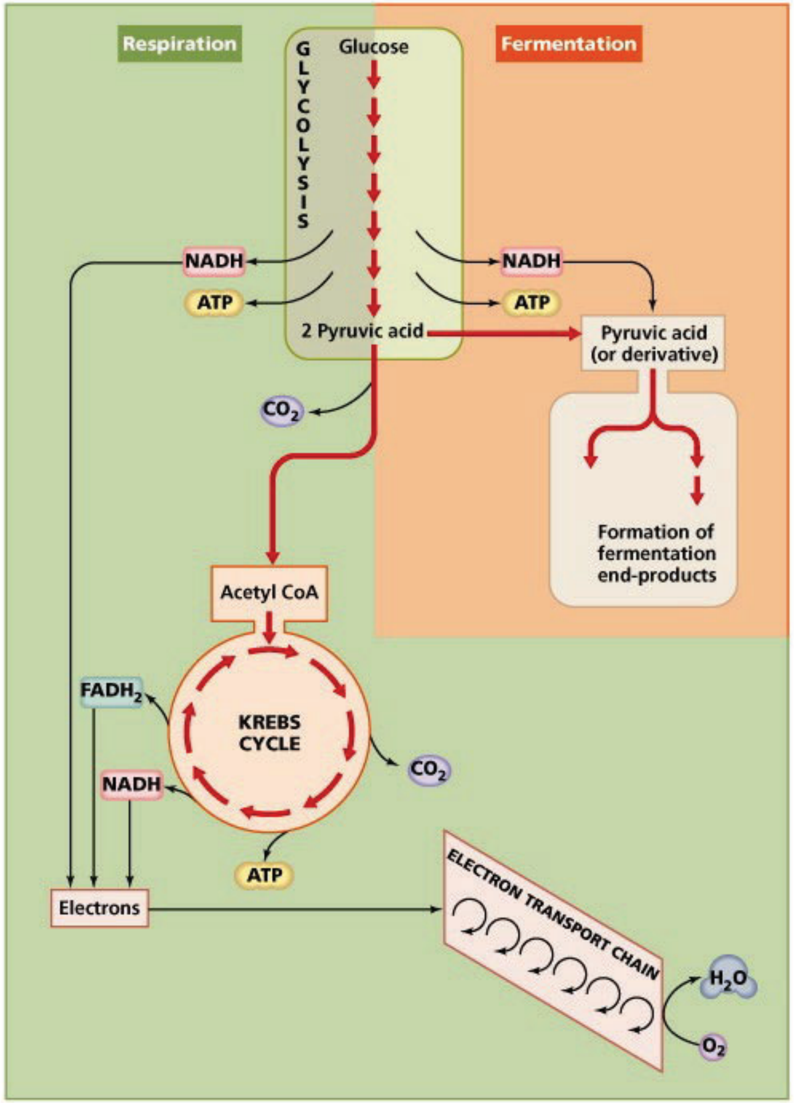
↳ anerobic process.
↳ but can take place under aerobic conditions
→ no kreb cycle or ETS or intermediate step
first glycolisis, then fermentation

Key Concept

To produce energy from glucose, microbes use two general processes: respiration and fermentation. Both usually start with glycolysis but follow different subsequent pathways.

Carbohydrate Catabolism

- The breakdown of carbohydrates to release energy
  - Glycolysis
  - Krebs cycle
  - Electron transport chain


Respiration
Fermentation
GLYCOLYSIS
Glucose
NADH
ATP
NADH
ATP
2 Pyruvic acid
Pyruvic acid (or derivative)
CO_2
Formation of fermentation end-products
Acetyl CoA
KREBS CYCLE
$FADH_2$
NADH
CO_2
ATP
Electrons
ELECTRON TRANSPORT CHAIN
H_2O
O_2

Alternatives to Glycolysis

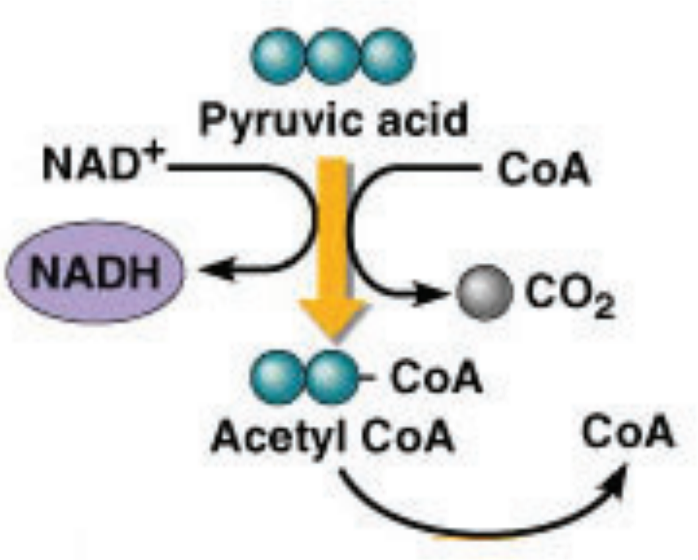
- Pentose phosphate pathway:
  - Uses pentoses and NADPH
  - Operates with glycolysis
- Entner-Doudoroff pathway:
  - Produces NADPH and ATP
  - Does not involve glycolysis
  - *Pseudomonas, Rhizobium, Agrobacterium*

Cellular Respiration

- Oxidation of molecules liberates electrons for an electron transport chain
- ATP generated by oxidative phosphorylation

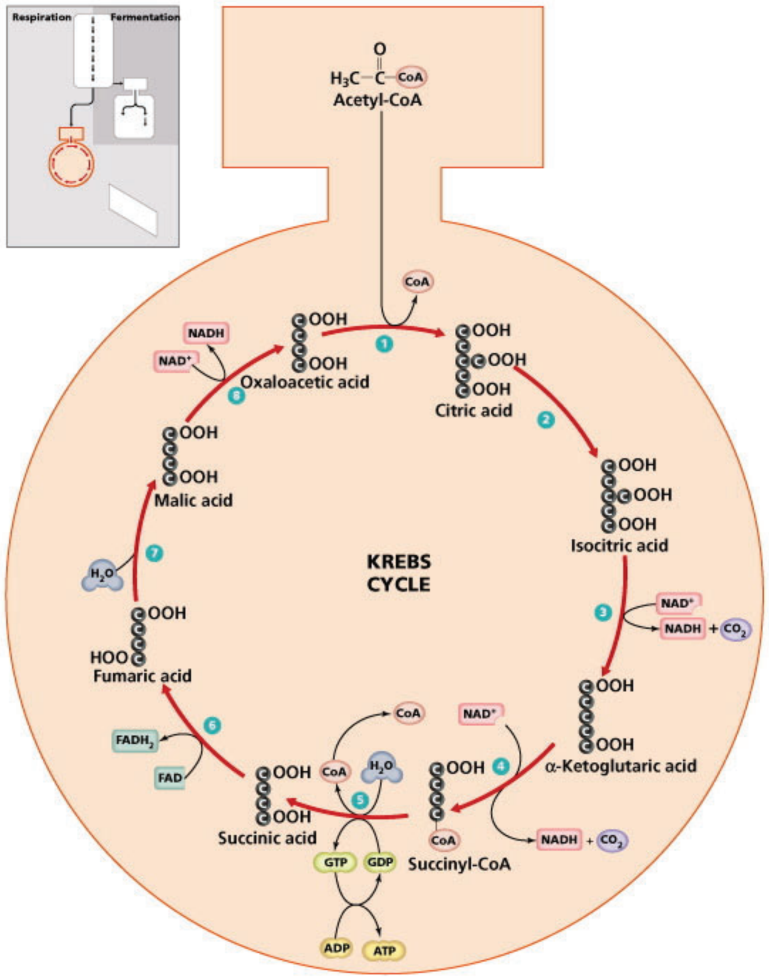
Intermediate Step

- Pyruvic acid (from glycolysis) is oxidized and decarboyxlated



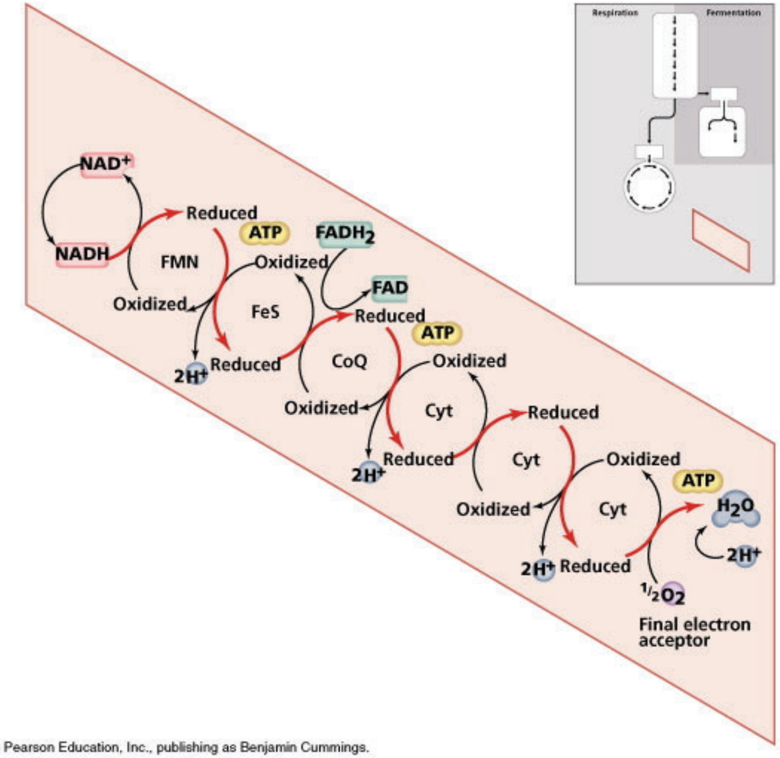
Krebs Cycle

- Oxidation of acetyl CoA produces NADH and $FADH_2$



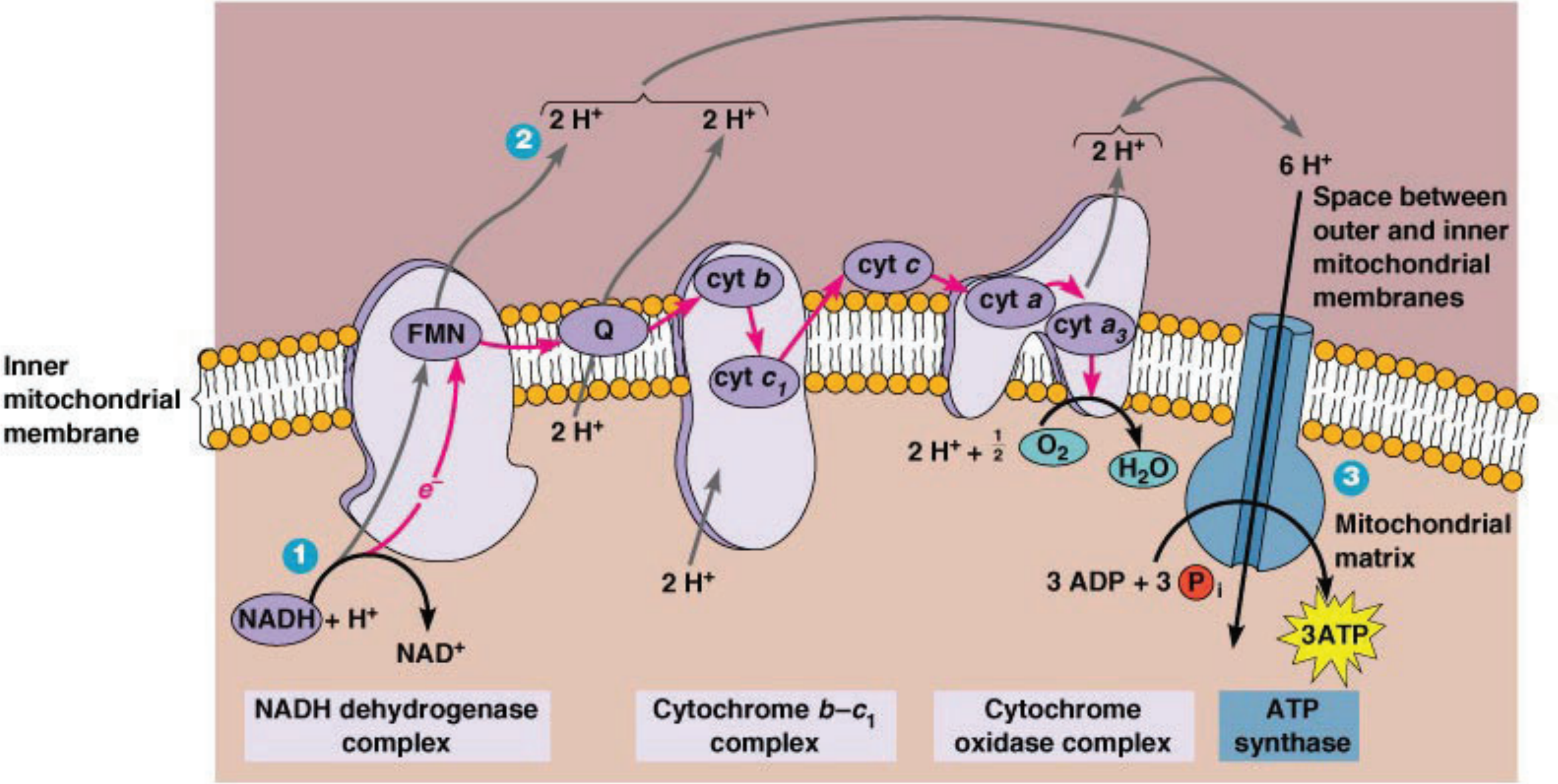
The Electron Transport Chain

- A series of carrier molecules that are, in turn, oxidized and reduced as electrons are passed down the chain.
- Energy released can be used to produce ATP by chemiosmosis.



Pathway	**Eukaryote**	**Prokaryote**
Glycolysis	Cytoplasm	Cytoplasm
Intermediate step	Cytoplasm	Cytoplasm
Krebs cycle	Mitochondrial matrix	Cytoplasm
ETC	Mitochondrial inner membrane	Plasma membrane

Chemiosmosis



- Energy produced from complete oxidation of 1 glucose using aerobic respiration

Pathway	**ATP produced**	**NADH produced**	**$FADH_2$ produced**
Glycolysis	2	2	0
Intermediate step	0	2	
Krebs cycle	2	6	2
Total	**4**	**10**	**2**

- ATP produced from complete oxidation of 1 glucose using aerobic respiration

Pathway	**By substrate-level phosphorylation**	**By oxidative phosphorylation**	
		From NADH	**From FADH**
Glycolysis	2	6	0
Intermediate step	0	6	
Krebs cycle	2	18	4
Total	**4**	**30**	**4**

- 36 ATPs are produced in eukaryotes.

Respiration

- Aerobic respiration: The final electron acceptor in the electron transport chain is molecular oxygen (O_2).
- Anaerobic respiration: The final electron acceptor in the electron transport chain is not O_2. Yields less energy than aerobic respiration because only part of the Krebs cycles operations under anaerobic conditions.

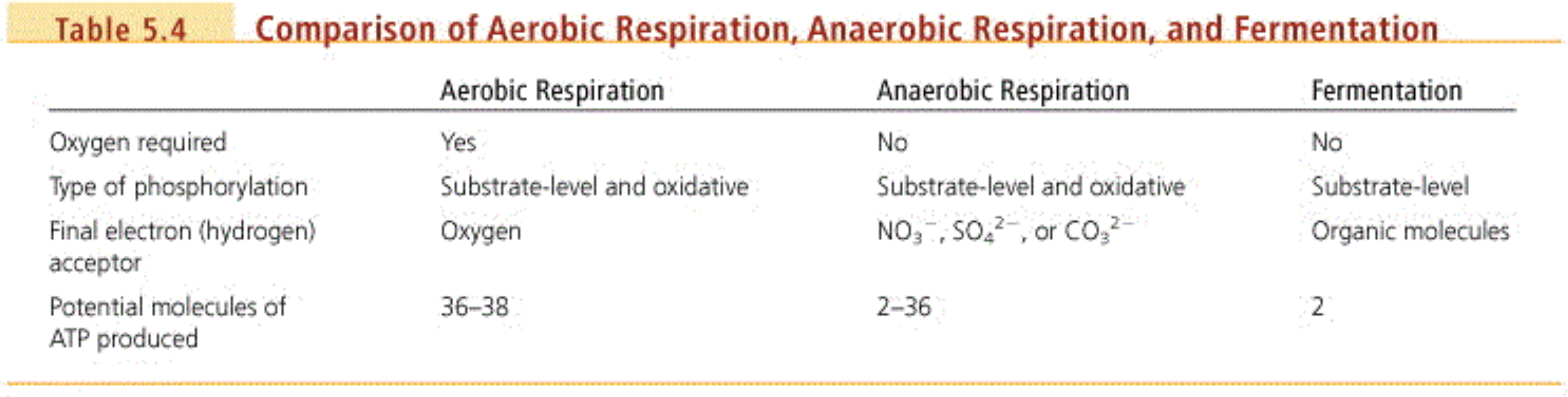


Table 5.4 Comparison of Aerobic Respiration, Anaerobic Respiration, and Fermentation

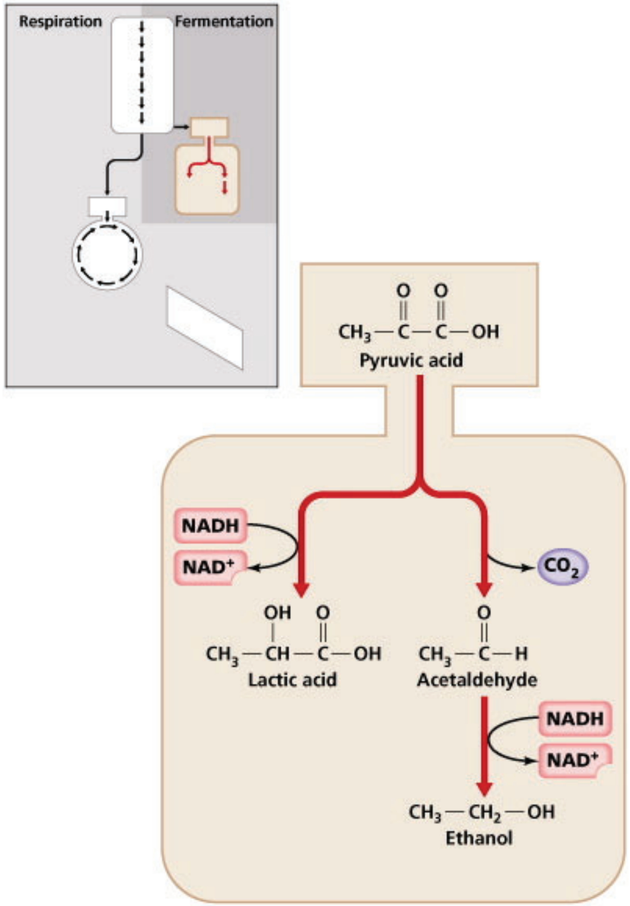
	Aerobic Respiration	Anaerobic Respiration	Fermentation
Oxygen required	Yes	No	No
Type of phosphorylation	Substrate-level and oxidative	Substrate-level and oxidative	Substrate-level
Final electron (hydrogen) acceptor	Oxygen	NO_3^-, SO_4^{2-}, or CO_3^{2-}	Organic molecules
Potential molecules of ATP produced	36–38	2–36	2

Anaerobic Respiration

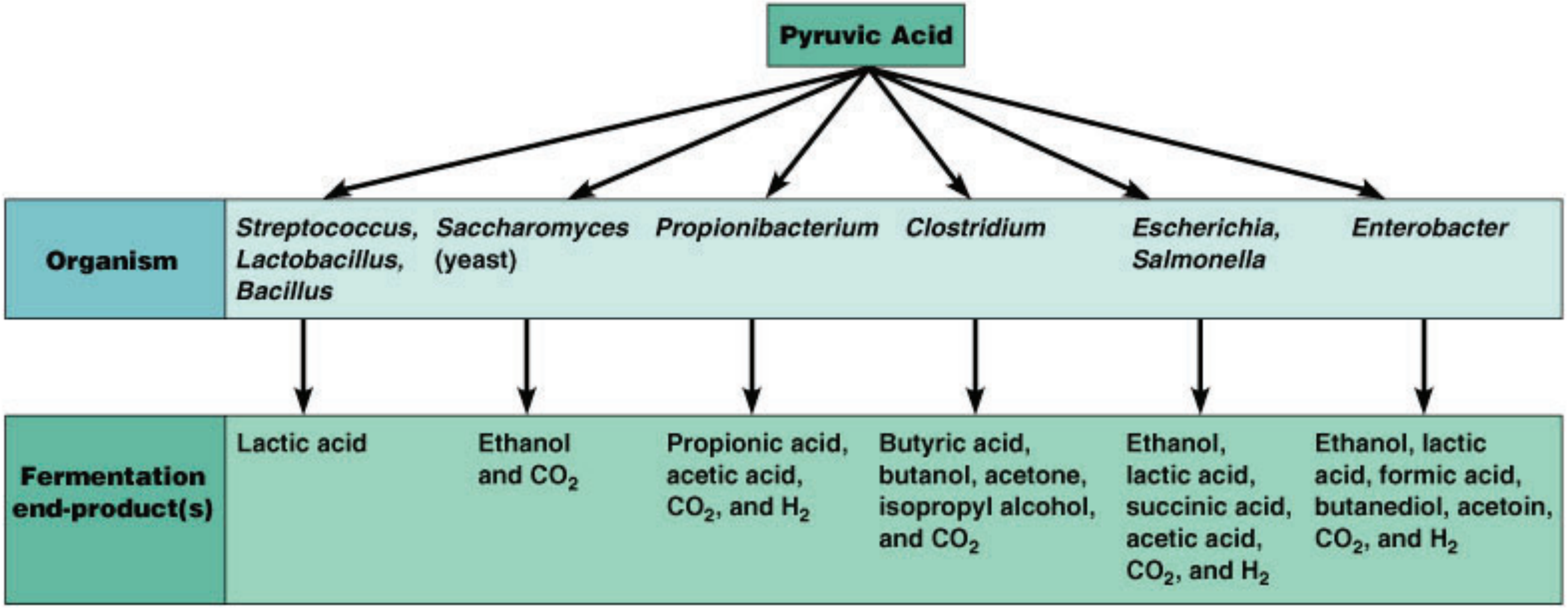
Electron acceptor	**Products**
NO_3^-	NO_2^-, $N_2 + H_2O$
SO_4^-	$H_2S + H_2O$
CO_3^{2-}	$CH_4 + H_2O$

Fermentation

- Releases energy from oxidation of organic molecules
- Does not require oxygen
- Does not use the Krebs cycle or ETC
- Uses an organic molecule as the final electron acceptor



Fermentation

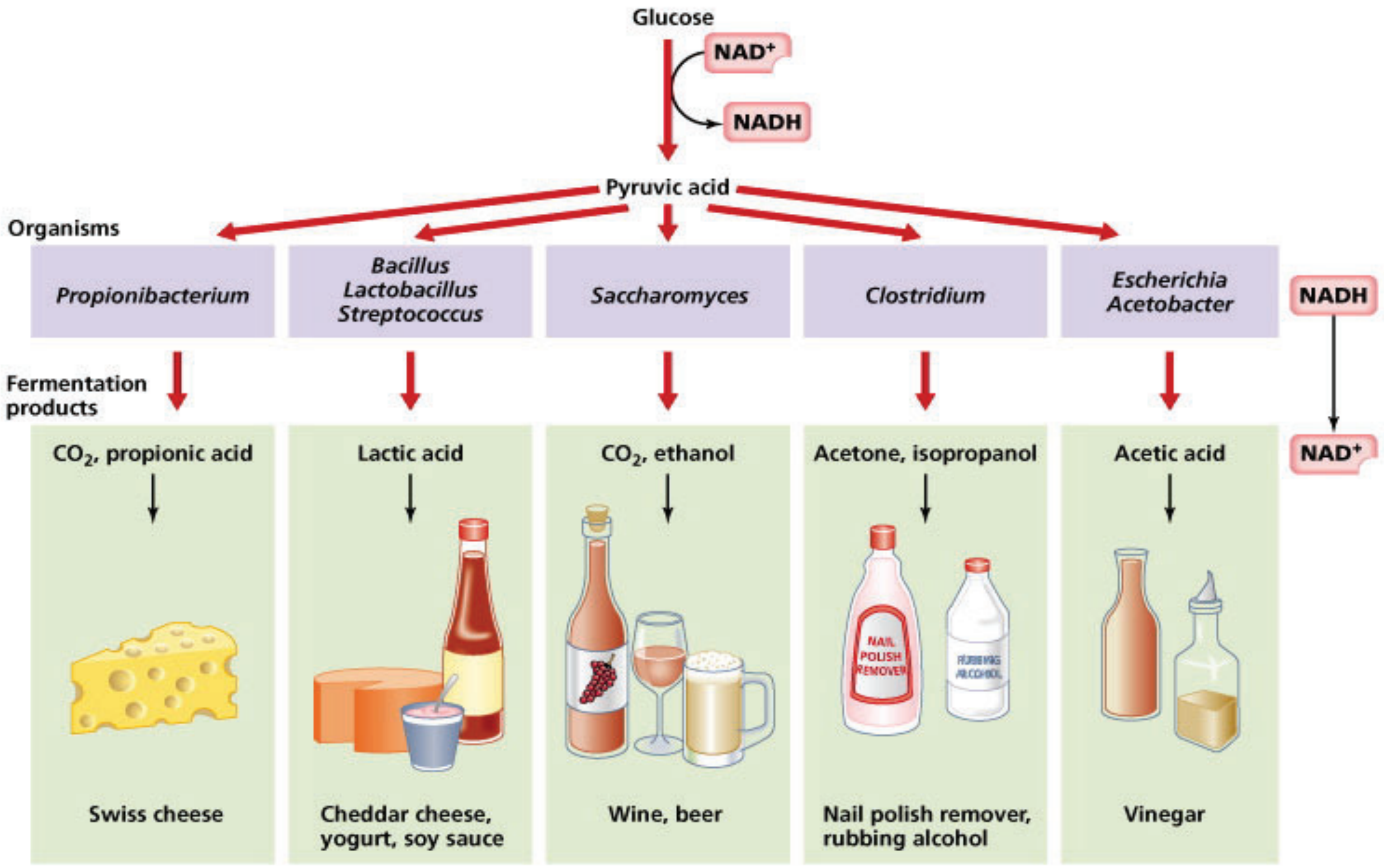


Pyruvic Acid

Organism	*Streptococcus, Lactobacillus, Bacillus*	*Saccharomyces* (yeast)	*Propionibacterium*	*Clostridium*	*Escherichia, Salmonella*	*Enterobacter*
Fermentation end-product(s)	Lactic acid	Ethanol and CO_2	Propionic acid, acetic acid, CO_2, and H_2	Butyric acid, butanol, acetone, isopropyl alcohol, and CO_2	Ethanol, lactic acid, succinic acid, acetic acid, CO_2, and H_2	Ethanol, lactic acid, formic acid, butanediol, acetoin, CO_2, and H_2

(b)

Fermentation Products



Glucose

NAD^+ → NADH

Pyruvic acid

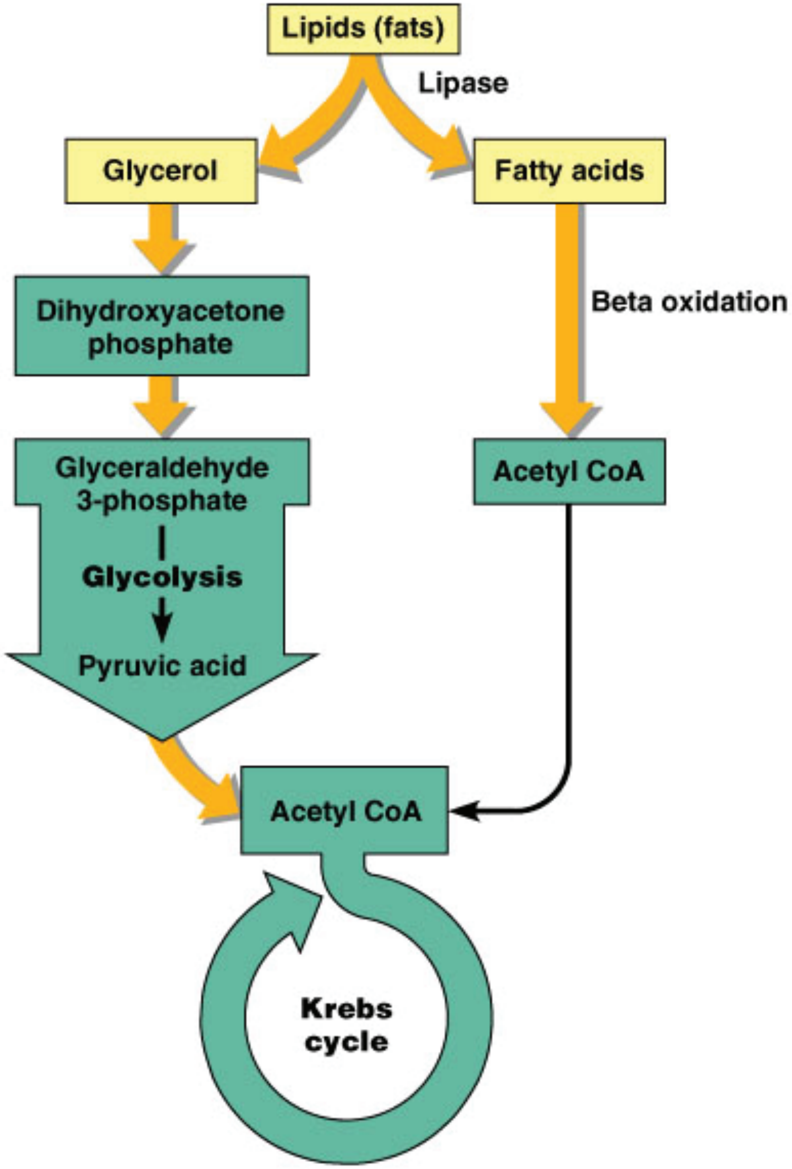
Organisms	*Propionibacterium*	*Bacillus* *Lactobacillus* *Streptococcus*	*Saccharomyces*	*Clostridium*	*Escherichia* *Acetobacter*
Fermentation products	CO_2, propionic acid	Lactic acid	CO_2, ethanol	Acetone, isopropanol	Acetic acid
	Swiss cheese	Cheddar cheese, yogurt, soy sauce	Wine, beer	Nail polish remover, rubbing alcohol	Vinegar

NADH → NAD^+

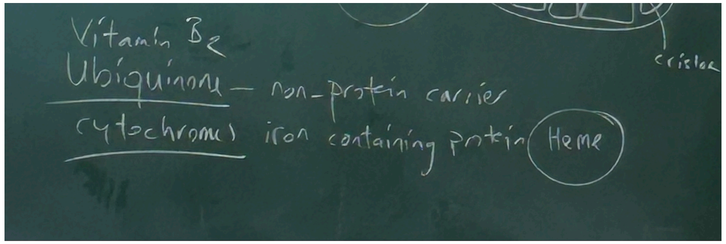
Fermentation

- Alcohol fermentation Produces ethyl alcohol + CO_2
- Lactic acid fermentation Produces lactic acid.
  - Homolactic fermentation Produces lactic acid only.
  - Heterolactic fermentation Produces lactic acid and other compounds.

Lipid Catabolism

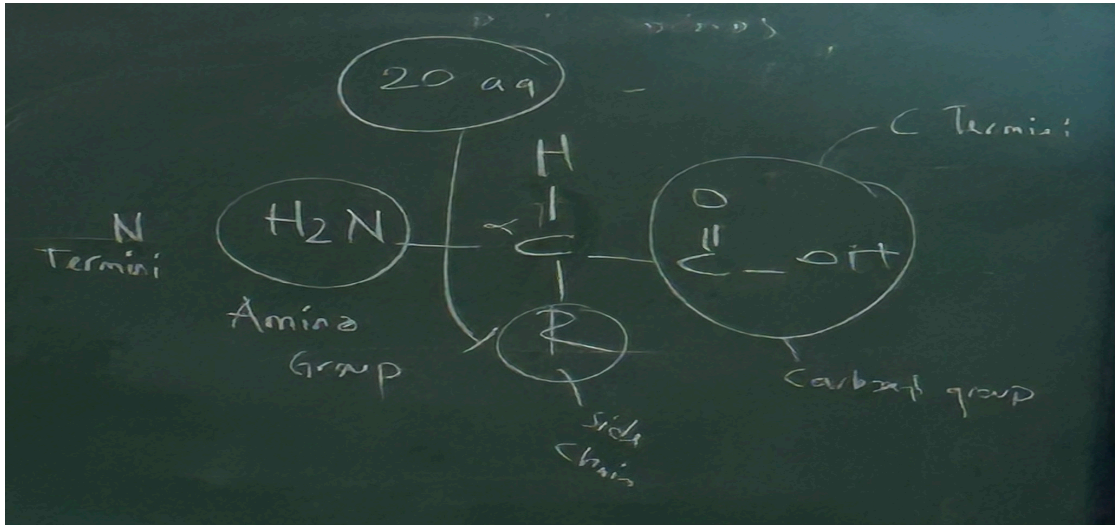


Protein Catabolism



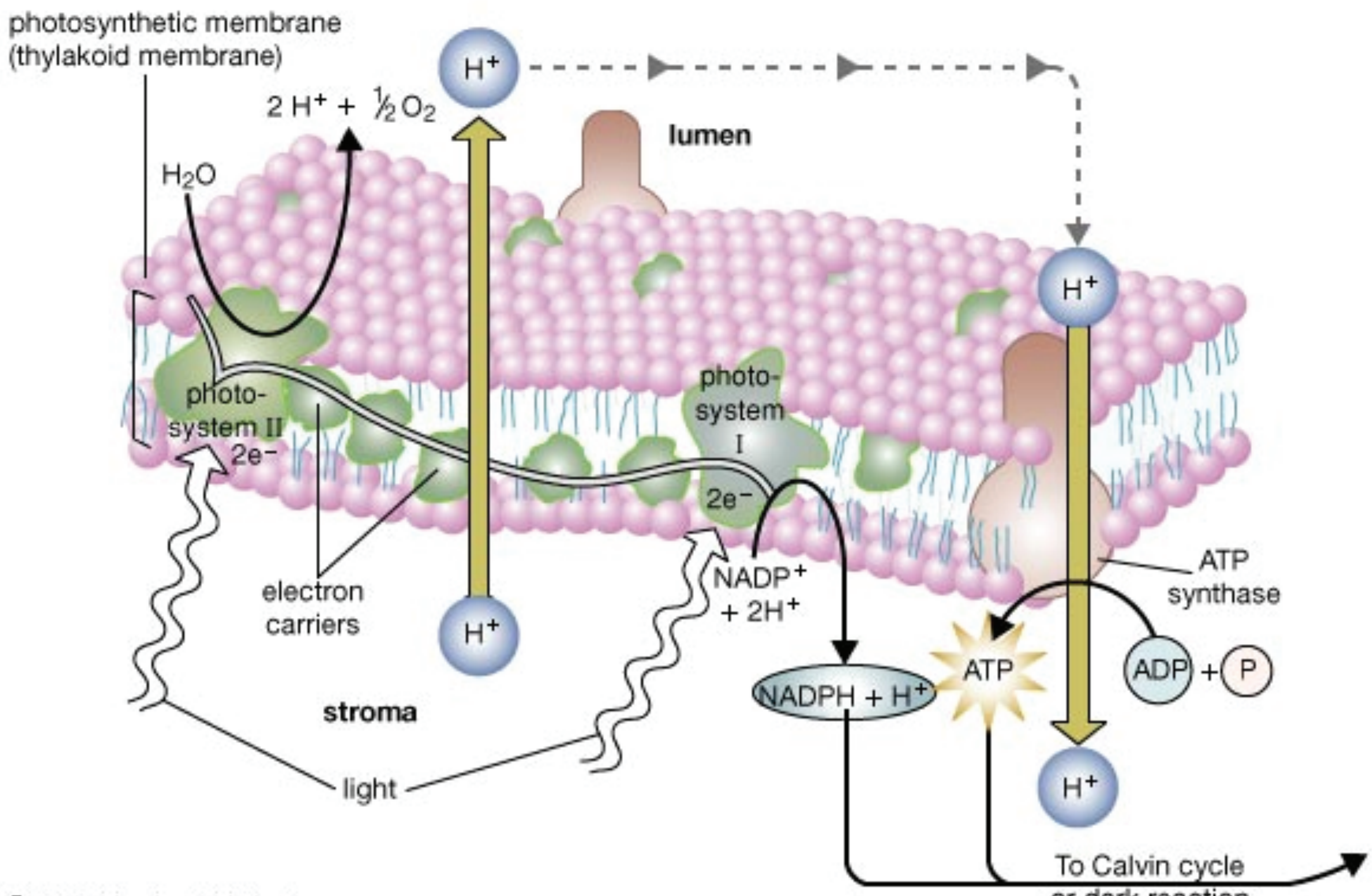
Protein $\xrightarrow{\text{Extracellular proteases}}$ Amino acids

$\xrightarrow{\text{Deamination, decarboxylation, dehydrogenation}}$ Organic acid → Krebs cycle



Photosynthesis

- Photo: Conversion of light energy into chemical energy (ATP)
  - Light-dependent (light) reactions
- Synthesis: Fixing carbon into organic molecules
  - Light-independent (dark) reaction, Calvin-Benson cycle
- Oxygenic:
  $6\ CO_2 + 12\ H_2O + \text{Light energy} \rightarrow C_6H_{12}O_6 + 6\ O_2 + 6\ H_2O$
- Anoxygenic:
  $CO_2 + 2\ H_2S + \text{Light energy} \rightarrow [CH_2O] + 2\ A + H_2O$

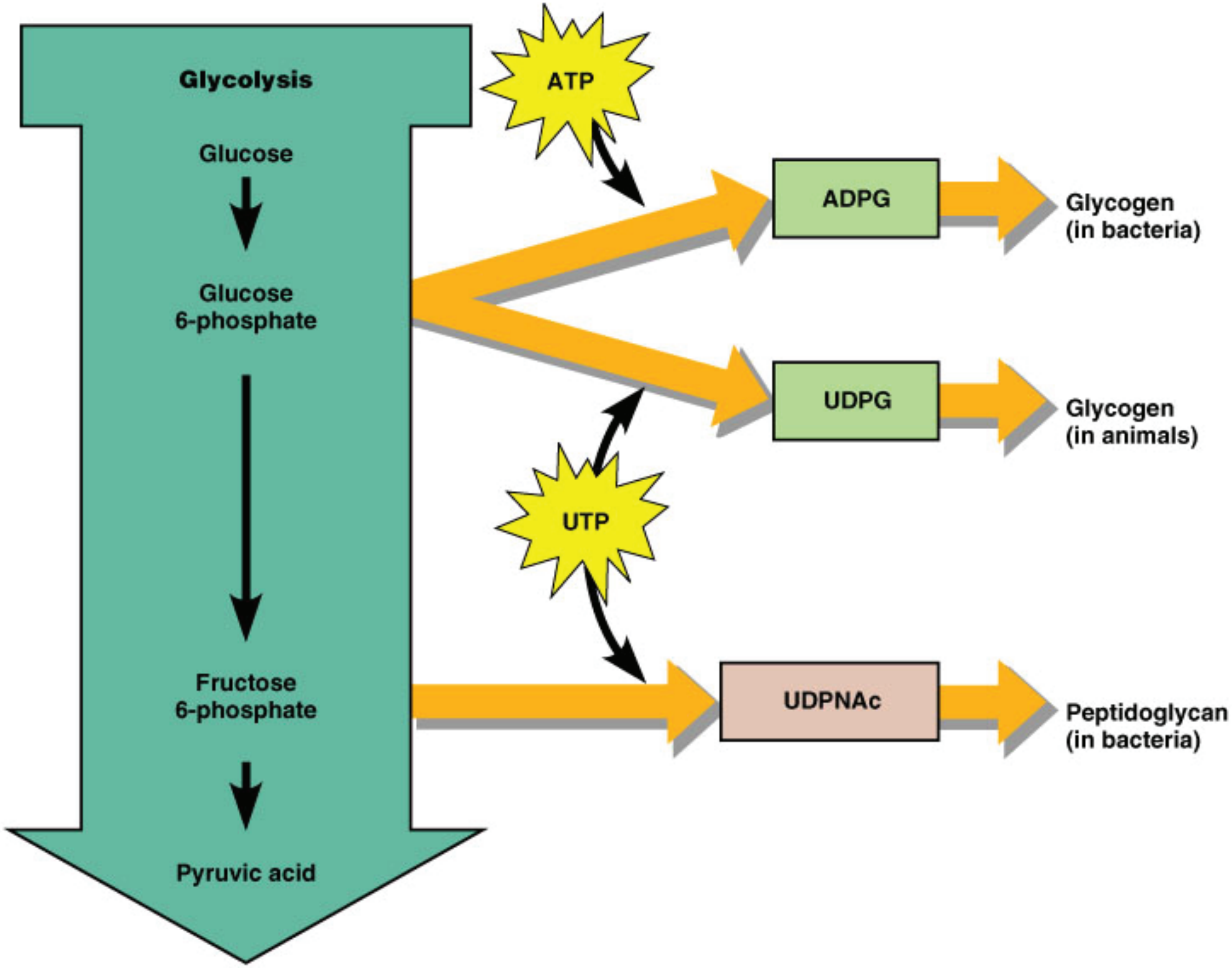

photosynthetic membrane
(thylakoid membrane)
$2 H^+ + \frac{1}{2} O_2$
H^+
lumen
H_2O
H^+
photo-
system II
$2e^-$
photo-
system
I
$2e^-$
electron
carriers
H^+
NADP$^+$
+ 2H$^+$
ATP
synthase
NADPH + H$^+$
ATP
ADP
+
P
H^+
stroma
light
To Calvin cycle
or dark reaction

Metabolic Diversity Among Organisms

Nutritional type	Energy source	Carbon source	Example
Photoautotroph	Light	CO_2	Oxygenic: Cyanobacteria plants. Anoxygenic: Green, purple bacteria.
Photoheterotroph	Light	Organic compounds	Green, purple nonsulfur bacteria.
Chemoautotroph	Chemical	CO	Iron-oxidizing bacteria.
Chemoheterotroph	Chemical	Organic compounds	Fermentative bacteria. Animals, protozoa, fungi, bacteria.

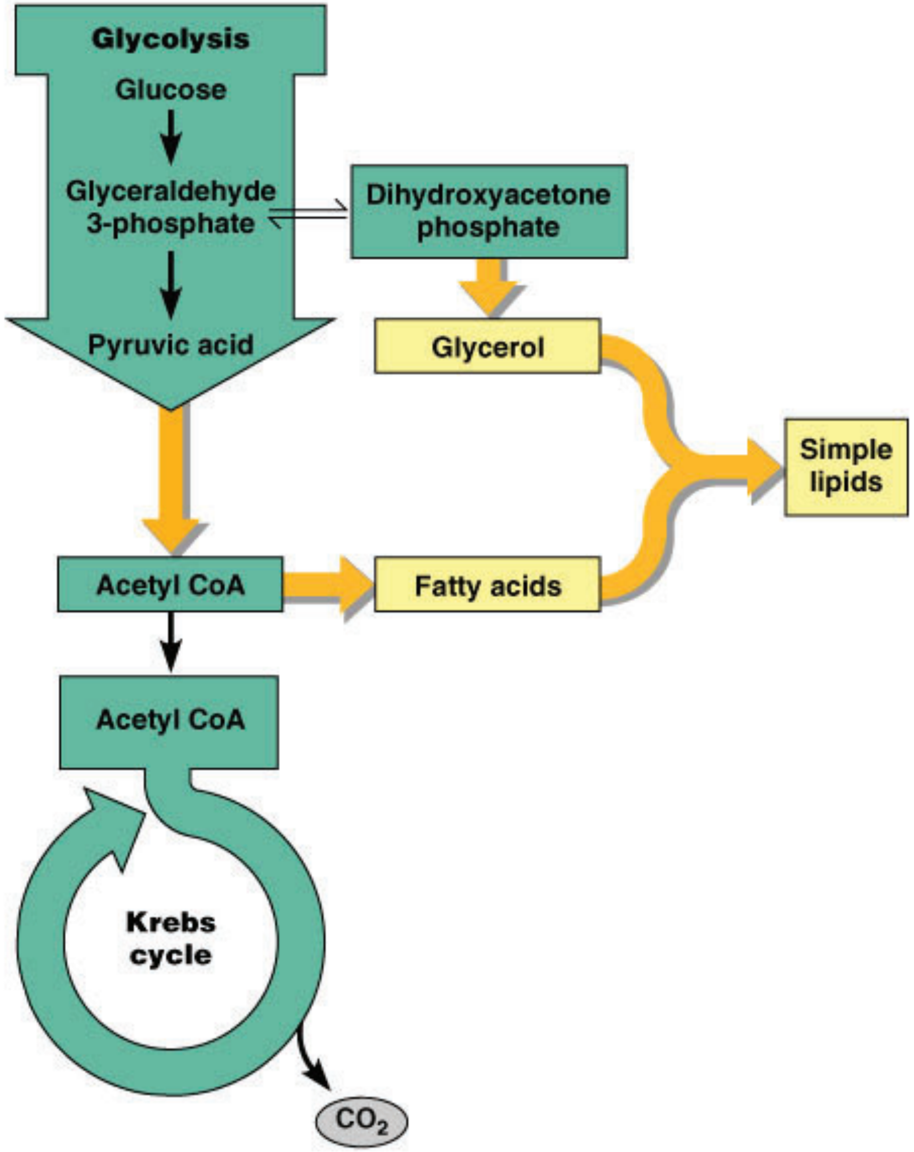
Metabolic Pathways of Energy Use

- Polysaccharide Biosynthesis



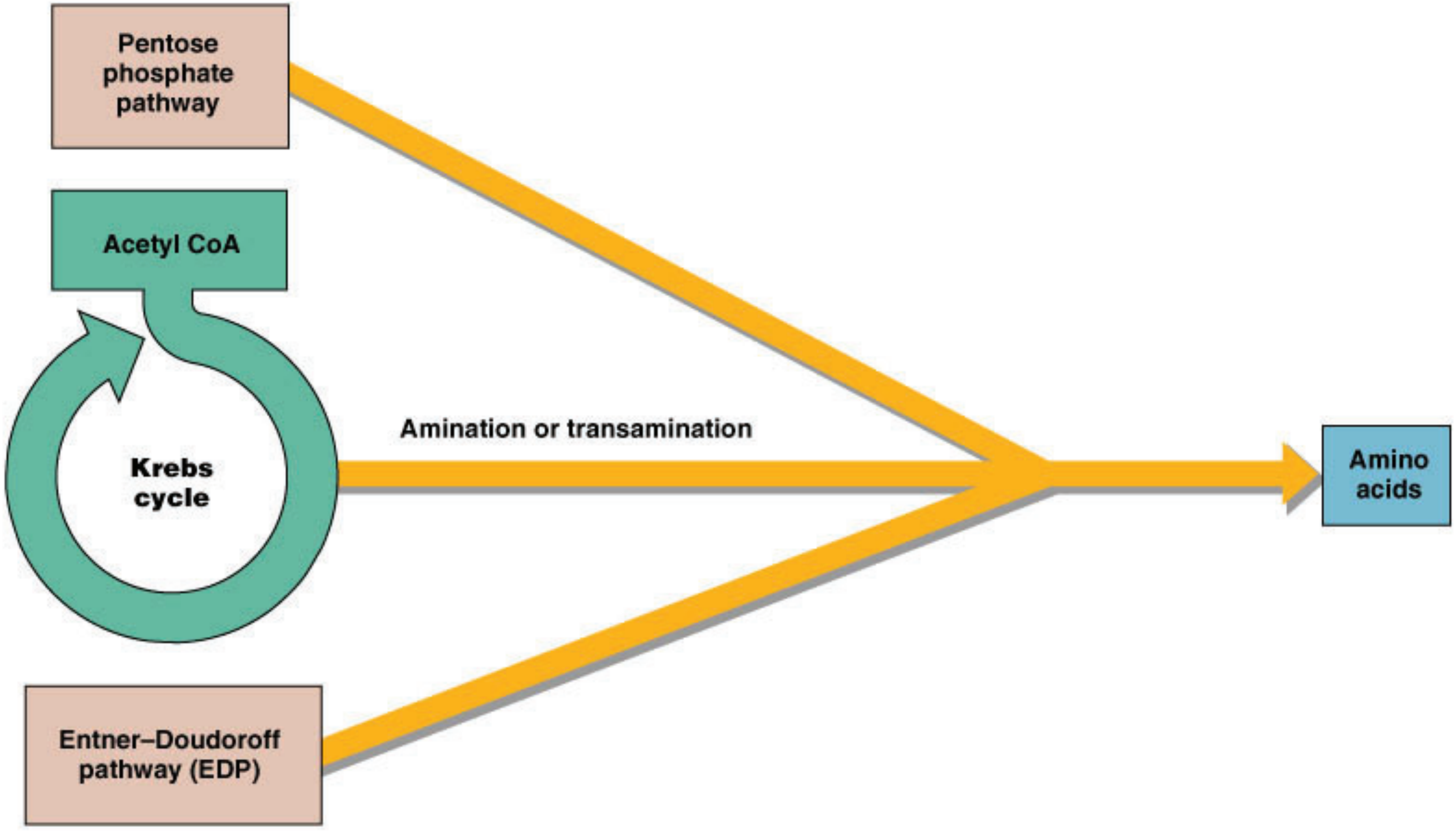
Metabolic Pathways of Energy Use

- Lipid Biosynthesis



Metabolic Pathways of Energy Use

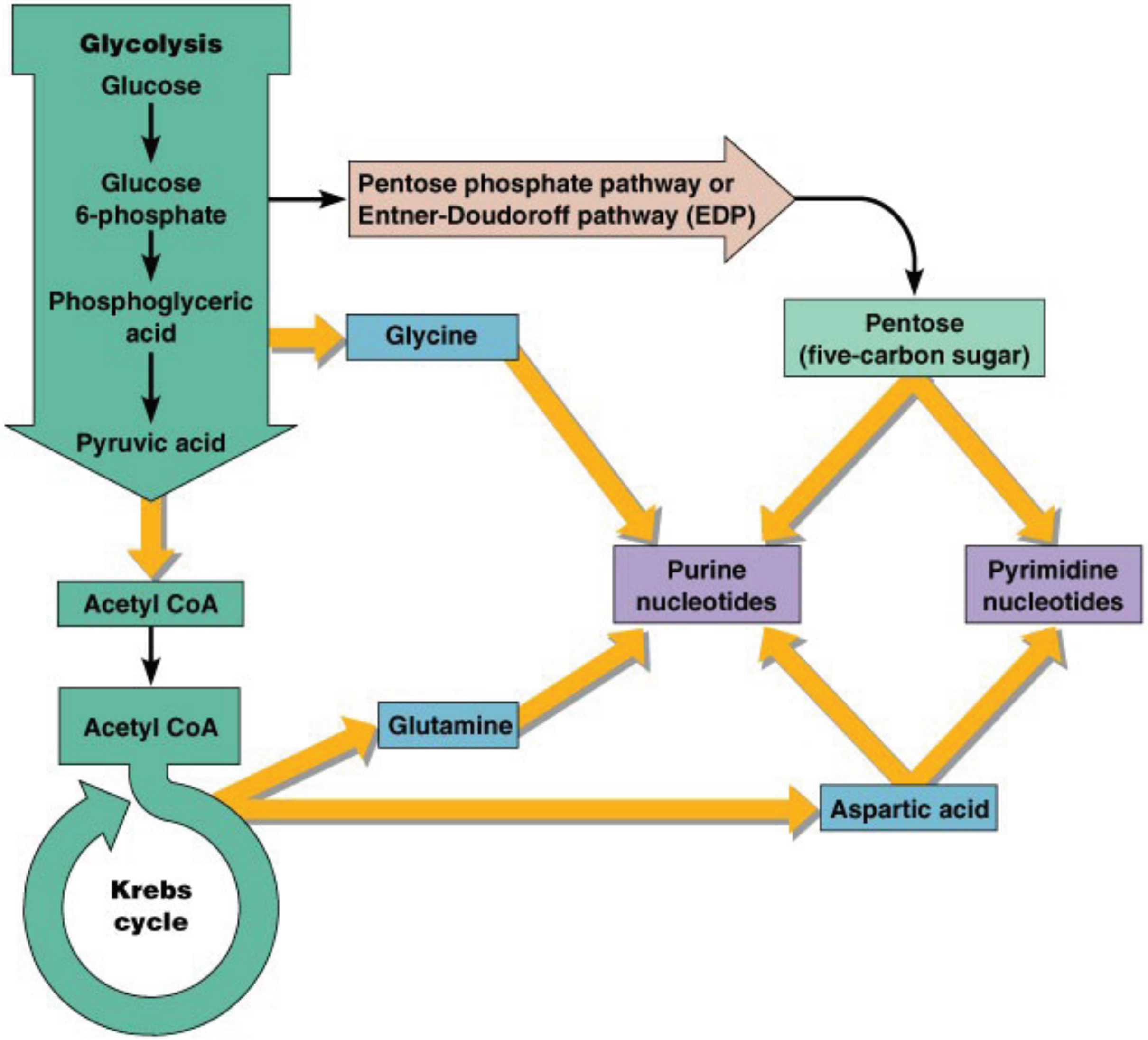
- Amino Acid and Protein Biosynthesis



(a) Amino acid biosynthesis

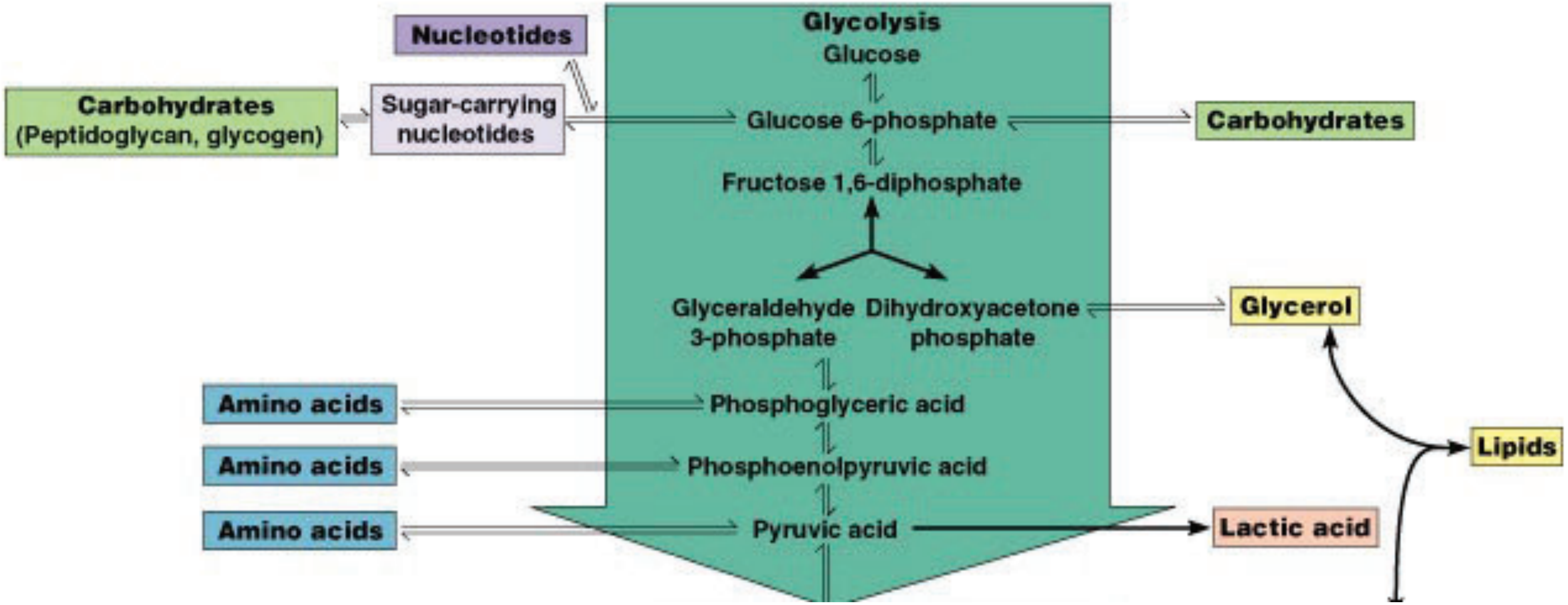
Metabolic Pathways of Energy Use

- Purine and Pyrimidine Biosynthesis

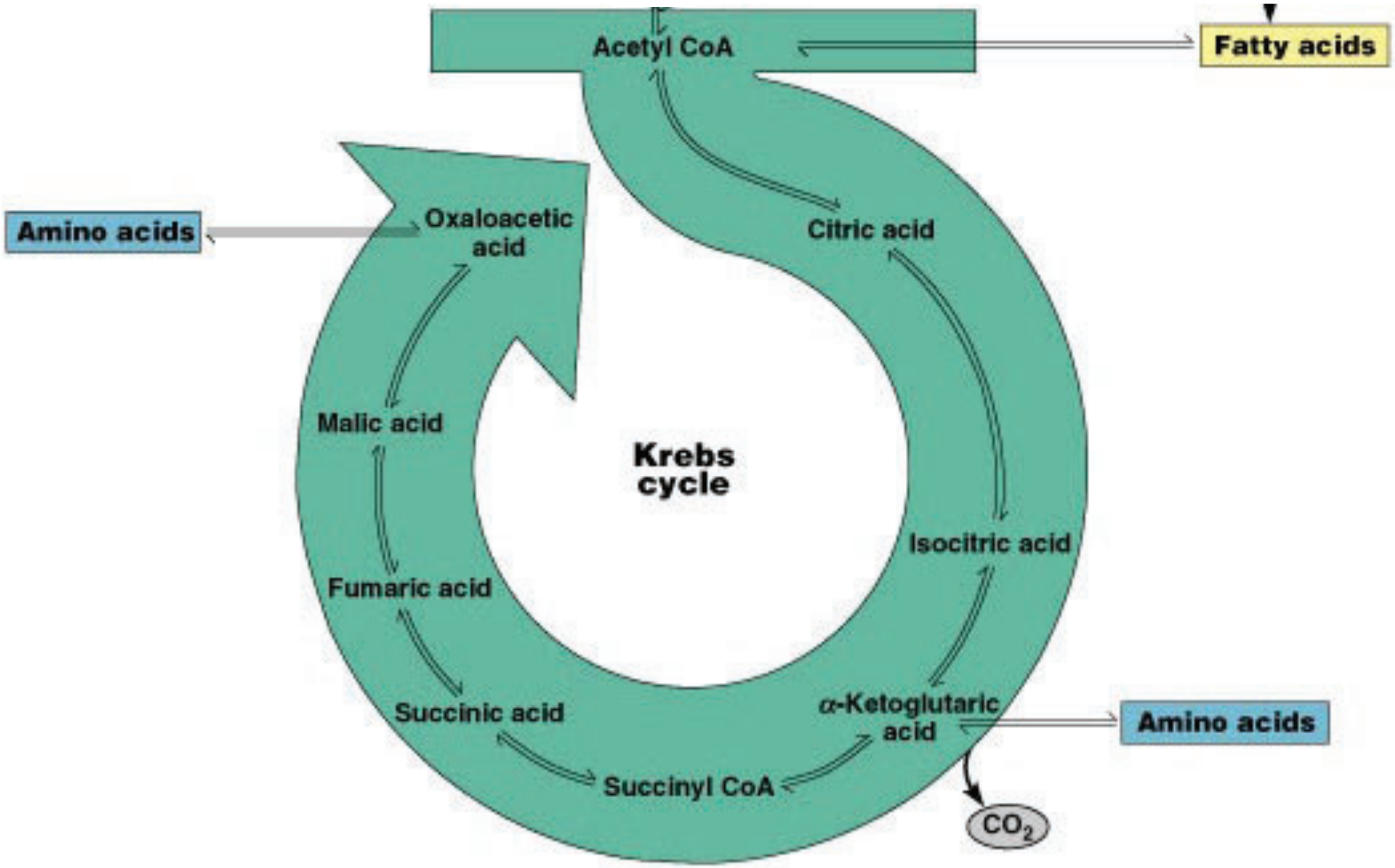


Amphibolic Pathways

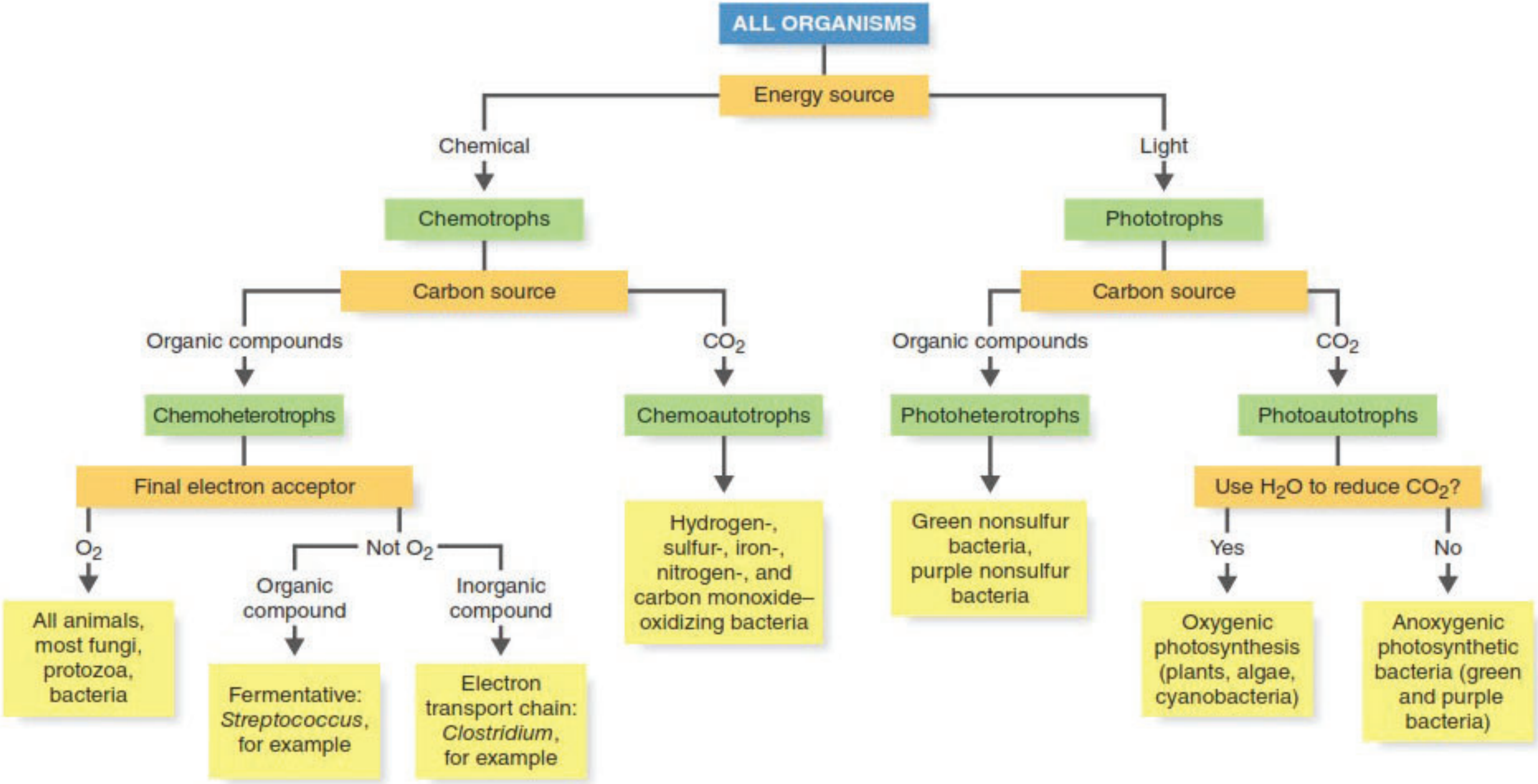
- Are metabolic pathways that have both catabolic and anabolic functions.



Amphibolic Pathways



In summary



ALL ORGANISMS

Energy source

Chemical

Chemotrophs

Carbon source

Organic compounds

Chemoheterotrophs

Final electron acceptor

O_2

All animals, most fungi, protozoa, bacteria

Not O_2

Organic compound

Fermentative: *Streptococcus*, for example

Inorganic compound

Electron transport chain: *Clostridium*, for example

CO_2

Chemoautotrophs

Hydrogen-, sulfur-, iron-, nitrogen-, and carbon monoxide–oxidizing bacteria

Light

Phototrophs

Carbon source

Organic compounds

Photoheterotrophs

Green nonsulfur bacteria, purple nonsulfur bacteria

CO_2

Photoautotrophs

Use H_2O to reduce CO_2?

Yes

Oxygenic photosynthesis (plants, algae, cyanobacteria)

No

Anoxygenic photosynthetic bacteria (green and purple bacteria)