Lecture 17: Cellular Respiration

Food → Energy (ATP)

1. Glycolysis
2. Krebs cycle
3. Electron Transport

Key: inputs / outputs

↳ mainly ATP

+ a few general details

↳ [multichoice mainly].

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39) Approximately how many ATP molecules are produced during the Electron Transport stage of cellular respiration?

(1 mark)

Answer: ________________

38) Choose the TRUE statement(s) about cellular respiration:

(2 mark)

- **A.** Most of the ATP from cellular respiration is produced by the electron transport chain.
- **B.** Under standard conditions, nearly 100% of chemical energy in food molecules is converted into ATP to carry out cellular work.
- **C.** When no oxygen is present, glycolysis cannot proceed.
- **D.** Glucose is oxidised in cellular respiration.

Answer: ___________________________

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44) ATP can also be generated in the absence of oxygen (i.e. anaerobic conditions), which involves the process of fermentation. Comment on the number of ATP molecules you would produce from just glycolysis alone, compared to aerobic respiration.

(1 mark)

Answer:

45) Which of the following statements is FALSE with regard to the electron transport chain?

(1 mark)

A. The electron transport chain occurs along the inner wall of the mitochondria
B. ATP Synthase uses the energy of the hydrogen ion gradient to generate ADP from ATP
C. Electrons are accepted by oxygen at the end of the transport chain
D. Potential energy stored in the hydrogen ion gradient is released when the hydrogen ions re-enter the mitochondria
E. The high energy electrons carried in NADH and $FADH_2$ are passed from molecule to molecule in the electron transport chain in a series of redox reactions

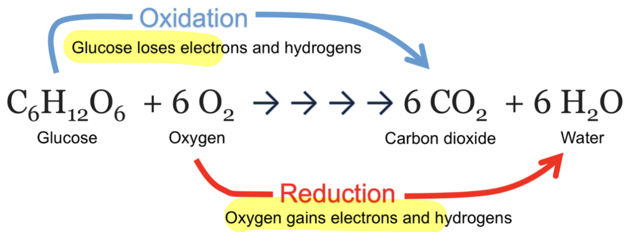
Answer: ________________

electrons

Some terminology: a **redox reaction** (reduction-oxidation) concerns reactions involving the **transfer of elections**. A key mnemonic is OIL-RIG: Oxidation Is Losing Elections, Reduction is Gaining Electrons.

During cellular respiration:

1. Glucose is **oxidised** (loses electrons and hydrogen).
2. Oxygen is **reduced** (accepts elections and hydrogen).



Cellular respiration as a redox reaction.

There are **three key stages of cellular respiration**:

1. **Glycolysis**: breakdown of glucose started.
2. **Krebs Cycle**: breakdown of glucose completed and carbon dioxide formed.
3. **Electron Transport**: energy from breakdown of glucose converted to ATP.

An overview is shown below; we will consider each of these in detail.

End L16

NAD and FAD? — 'Coenzymes' ('helper molecules') L17

1 & 2: load buses — Think "electron shuttles/buses" NAD, FAD (unloaded form)

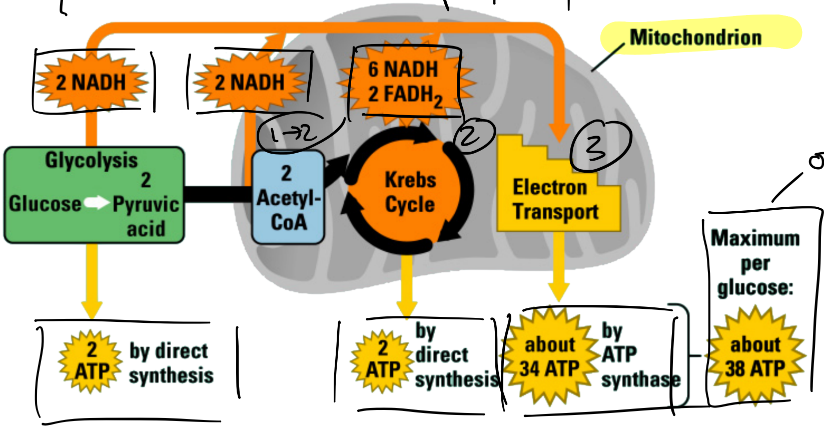
→ NADH & FADH$_2$ are loaded forms

(have more hydrogens & electrons)

3: unload — → unload to get energy

unload buses → fill ATP

Load buses



overall: 38 ATP

2 in
4 out
2 net.

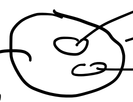
Figure 25: Stages of cellular respiration. During cellular respiration, 1 molecule of glucose creates ~38 molecules of ATP. One cell can have 1000-2000 mitochondria producing many energy-rich ATP molecules.

1. 2 ATP (Net) + 2NADH
↓ [+ 2NADH (1→2)]
2. 2 ATP + 6 NADH + $2FADH_2$
↓
3. 34 ATP

38 ATP

Key: ATP input/outputs

3.7.1 Glycolysis



Glycolysis is a series of nine reactions in the cytosol of the cell that **begins the breakdown of glucose**. It took about 100 years to discover and elaborate the full pathway!

not in mitochondria.

The **inputs and outputs** are illustrated below.

(1)

Initial 'splitting' of glucose, involving a series of 9 reactions

Input

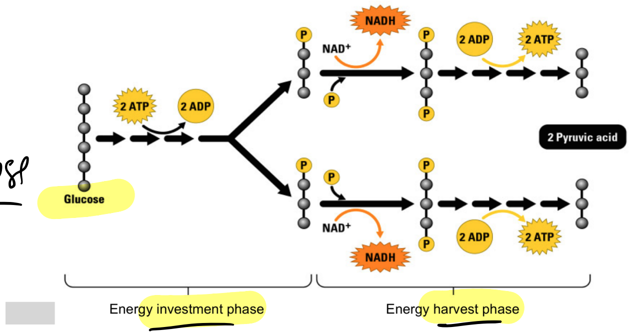
glucose + 2 ATP + 2 NAD+

Output

2 pyruvic acid + 4 ATP (2 ATP net) + 2 NADH

Free energy = -598 kJ/mol

1 glucose



→ 'preprocess' via coenzyme A → [2 acetic acid] → Krebs

See Fig 25.

Figure 26: Glycolysis mechanism.

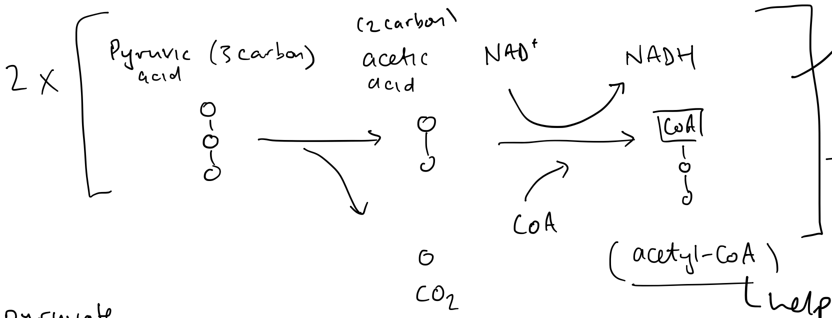
Key: invest: 2 ATP

output: 4 ATP + 2 NADH ('loaded buses')

⇒ Net: [2 ATP + 2 NADH]

↳ outside of mitochondria, in cell cytoplasm.

(1→2) Preprocessing step: (ready for Krebs in mitochondria)



→ [2 NADH]

→ to Krebs

└ helps transport.

CoA: co-enzyme A.

(pyruvate oxidation
↳ takes place in mitochondrial matrix)

3.7.2 Krebs Cycle

in matrix of mitochondria.

2

Also known as the 'citric acid cycle' occurs in the mitochondria and completes the energy extraction from glucose

Input **Output**

note → 2 Acetic acid + 2 ADP + 6 NAD++ 2 FAD 4 CO2 + 2 ATP + 6 NADH + 2 FADH2

(via pre processing step).

Free energy = -2265 kJ/mol

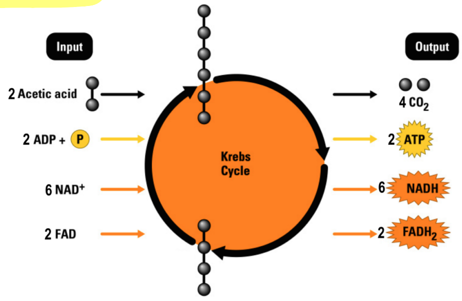


Figure 27: Krebs cycle stages.

Key:

Outputs:

$\boxed{2\,ATP}$ by direct synthesis

$\boxed{6\,NADH + 2\,FADH_2}$ 'loaded' electron buses

Notes: • 6 carbon 'citrate' is an intermediate part of cycle, hence also known as 'citric acid cycle'

• These carbon compounds are being continuously recycled

↳ no net production of eg citric acid etc.

3.7.3 Electron Transport – unload the buses!

Most of the energy is now in the electrons within the carriers NAD+ and FAD. The **electron transport chain** completes the process of cellular respiration and generates ~34 ATP molecules

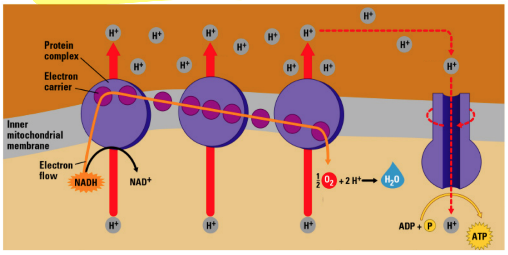
2+2+6 NADH
0+0+2 $FADH_2$

Input

10 NADH, 2 FADH2

Output

34 ATP



– intermembrane space
– inner mitochondrial membrane.

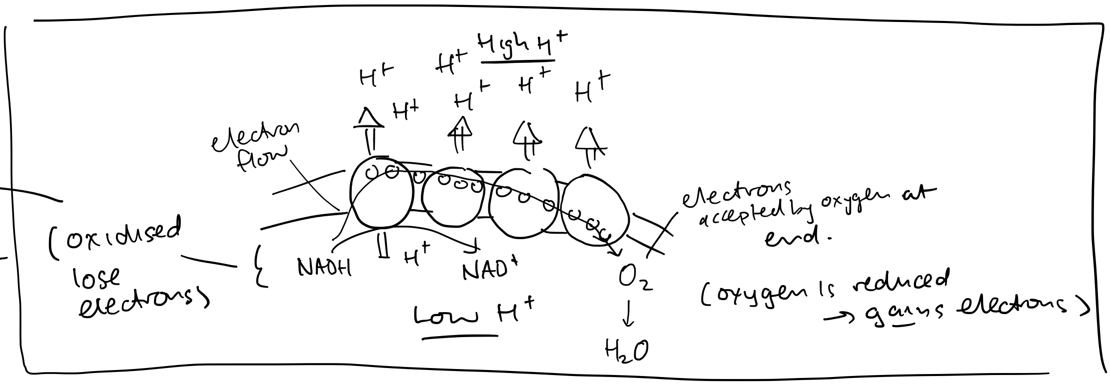
Electron transport stages.

Key: inputs: 10 NADH + 2 $FADH_2$ ⟶ $\boxed{\text{Output: 34 ATP}}$

Notes:

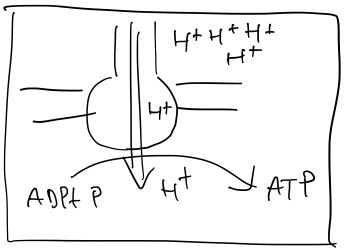
- Electrons are 'unloaded' 'through' pumps, accepted at end by oxygen. (hence redox reaction)
- Used to pump protons (hydrogen ions) across inner mitochondrial membrane

oxidation of NADH:
$NADH \rightarrow NAD^+ + H^+ + 2e^-$



- The H^+ gradient is used to 'power' the ATP-ase enzyme which phosphorylates ADP to ATP.

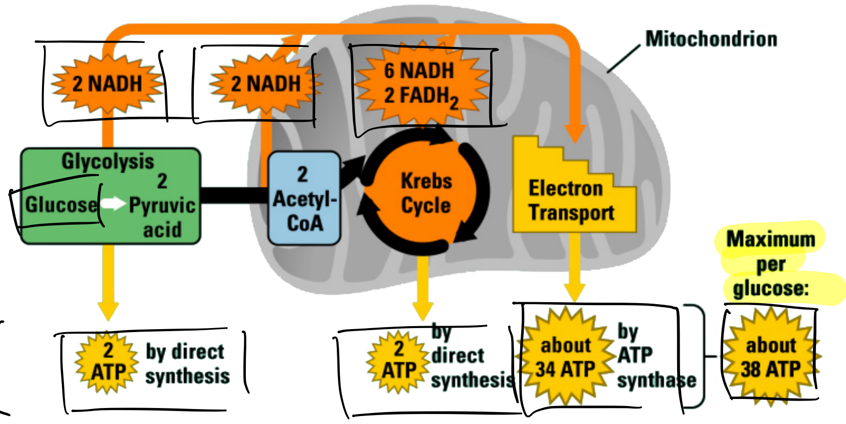
ie ADP + P ⟶ ATP
'recharges' (requires energy)



3.7.4 Cellular efficiency

Consider again the overall picture from before.

Net ATP



Stages of cellular respiration.

We can calculate the **efficiency** of the conversion of food to ATP energy.

Cellular efficiency

Free energy available from glucose:

$$\Delta G = -2862 \text{ kJ/mol}$$

cellular respiration : 38 ATP produced / glucose molecule

Free energy / ATP : $\Delta G = -29$ kJ/mol

$$\text{Efficiency} = \frac{\text{output}}{\text{input}} = \frac{38 \times (-29)}{-2862} \frac{\text{kJ/mol}}{\text{kJ/mol}}$$

$$\Rightarrow \boxed{\text{efficiency} \approx 38\%}$$

3.7.5 Just glucose?

No! Cellular respiration can use many different food molecules to generate ATP.

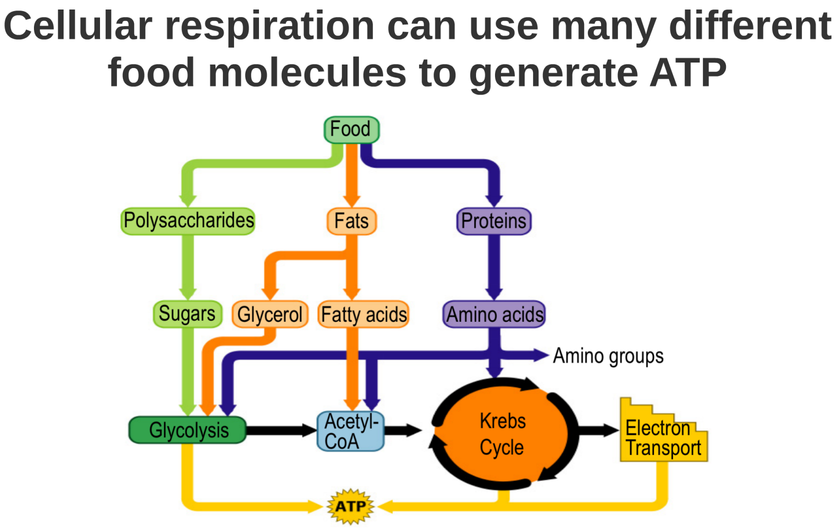


Figure 28: Alternative pathways for cellular respiration.

3.8 Fermentation

How about just cellular respiration? No again! For example the process of **fermentation** is an *alternative* way to generate ATP. In particular, while parts of cellular respiration require oxygen - i.e. are aerobic - fermentation does not.

While stage one of cellular respiration, glycolysis, **doesn't require oxygen**, it only produces 2 ATP (c.f. 38 ATP)!

Fermentation allows glycolysis to continue and can generate ATP without oxygen present, i.e. under **anaerobic conditions**.

Fermentation

- NADH produced but can't be oxidised in usual way (ie via O_2 in electron transport)
- Instead, use NADH to reduce pyruvic acid to eg
  - lactic acid (human muscle cells)
  - ethanol & CO_2 (yeast)

For example, during intense exercise, **human muscle cells** may not receive enough O_2. Fermentation then proceeds, and leads to the production of *lactic acid*. Note: lactic acid is not the cause of the burning sensation you might feel during intense exercise (actually, lactic acid tends to *counteract* this).

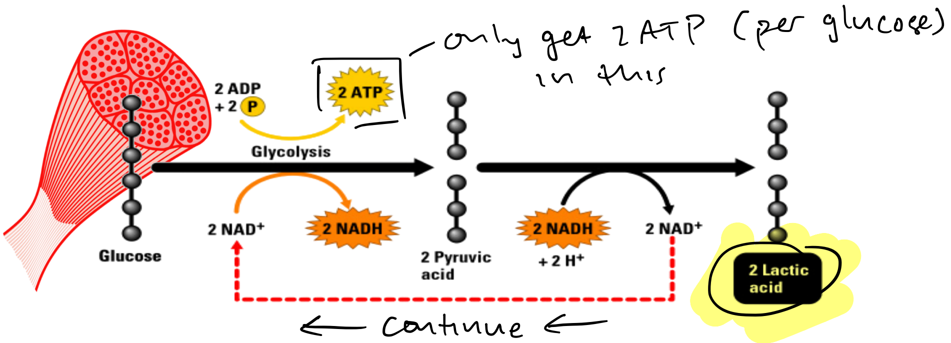
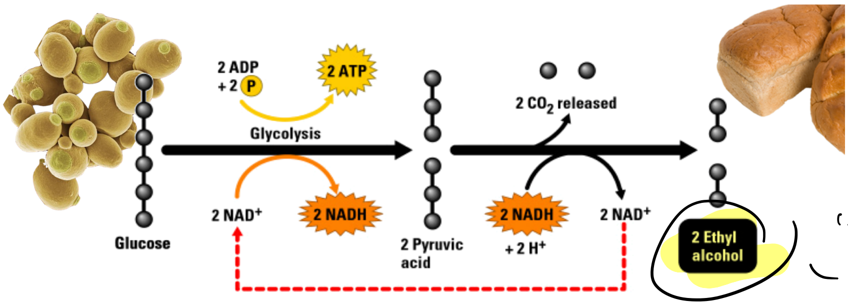


Figure 29: Human muscle cells. Oxygen is supplied to your muscles via the blood stream for aerobic cellular respiration to take place and make ATP. However, during exercise, the supply of oxygen can be insufficient and ATP must be made anaerobically, leading to lactic acid as a by-product.

Micro-organisms/bacteria (e.g. yeast) can perform *both* respiration and fermentation.

The 'waste' product of such processes are often the *desired* product: e.g. alcohol, biofuels etc.



'waste': ← often desired product!

Figure 30: Fermentation processes in micro-organisms.

Example Problems 8: Respiration and Fermentation

1. Which of the following TWO statements about respiration are TRUE?

   A. ? Oxygen gas is reduced during cellular respiration. ✓ (RIG)

   ~~B.~~ Fermenting yeast cells produce lactic acid during bread making.

   ~~C.~~ The Krebs Cycle produces citric acid. (not net)

   D. Glycolysis requires an initial input of energy to split glucose. ✓ (investment phase)

2. Which of the following statements is FALSE with regard to the electron transport chain?

   ~~A.~~ The electron transport chain occurs along the inner wall of the mitochondria. ✓

   B. ATP Synthase uses the energy of the hydrogen ion gradient to generate ADP ? from ATP. ✗

   ~~C.~~ Electrons are accepted by oxygen at the end of the transport chain. ✓

   ~~D.~~ Potential energy stored in the hydrogen ion gradient is released when the hydrogen ions re-enter the mitochondria. ✓

   ~~E.~~ The high energy electrons carried in NADH and $FADH_2$ are passed from molecule to molecule in the electron transport chain in a series of redox reactions. ✓

3. ~~4.~~ ATP can also be generated in the absence of oxygen (i.e. anaerobic conditions), which involves the process of fermentation. Comment on the number of ATP molecules you would produce from just glycolysis alone, compared to aerobic respiration.

   (2 vs 38

Answers

1. A & D
2. B
3. Only get 2 ATP from anaerobic fermentation cf. 38 ATP from aerobic respiration

FIN.