

Recall:

Overview of Part II [Energy] Material

Split into three related sections

✓ 5. Basic Physics of Energy (~4/5 lectures)

- Sources & consumption of energy
- Forms of energy, units etc
- Basic balance calculations

✓ 6. Basics of Energy Transfer (~6/7 lectures)

- Thermodynamics
- More sophisticated balance calculations etc.

Here →

7. Basics of Biological Energetics (~4/5 lectures)

- How do animals, cells etc store & use energy

Lecture 15

(7.5, 7.6, 7.7 in book)

ATP as energy currency of cell

Topics

chemical kinetics

catalysts & enzymes

what you
should be
able to
do

understand the role &
use of ATP in driving
cellular processes

calc. reaction rates & interpret
chemical kinetics figures

understand the role of &
factors affecting catalysts/
enzymes

Examples

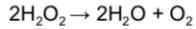
40) Which of the following statements about the molecule adenosine triphosphate (ATP) are FALSE?

(1 mark)

- W. ATP drives cellular work by transferring a phosphate group to a recipient molecule.
 - X. Almost 100% of the chemical energy in food molecules is converted into ATP to carry out cellular work.
 - Y. When an ATP molecule is used for cellular work, the remaining ADP and phosphate can be recycled to make another ATP.
 - Z. The generation of energy-rich ATP molecules during cellular respiration relies on producers harnessing light energy during photosynthesis.
- A. W only
 - B. Y and Z
 - C. X and Z
 - D. X only
 - E. W and X

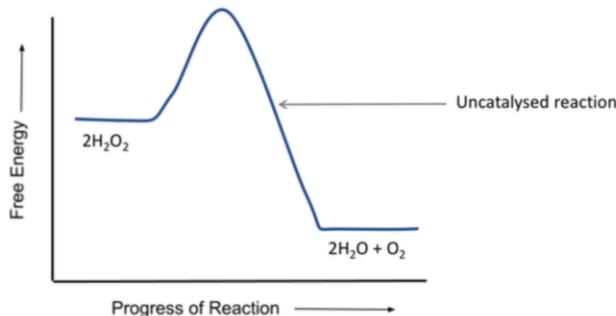
Answer: _____

41) Enzymes are biological catalysts. The enzyme 'catalase' catalyses the following reaction of H₂O₂ (hydrogen peroxide) in cells:



- a. The reaction co-ordinate diagram below shows the uncatalysed breakdown of hydrogen peroxide to water and oxygen. Draw in the curve for the catalysed reaction and label the activation energy for both the catalysed and uncatalysed reactions.

(2 marks)



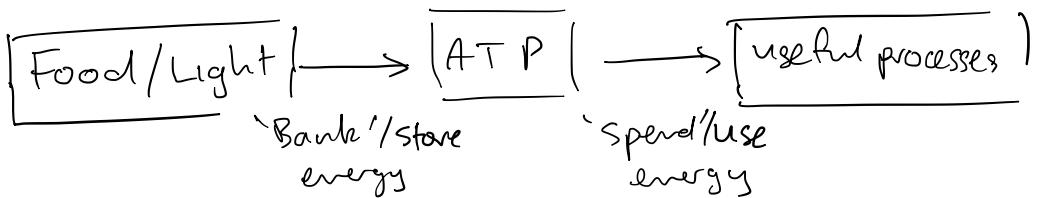
- b. Various factors affect the activity of enzymes. Explain how surrounding temperatures of 20 °C, 37 °C and 50 °C would affect the activity of catalase.

(2 marks)

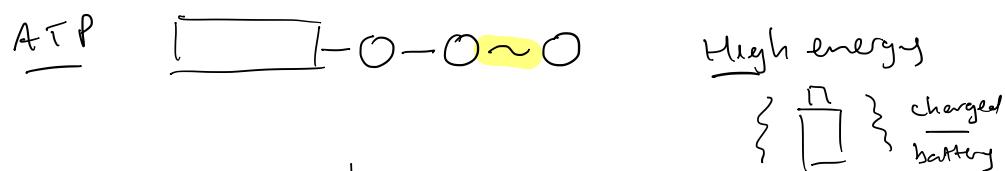
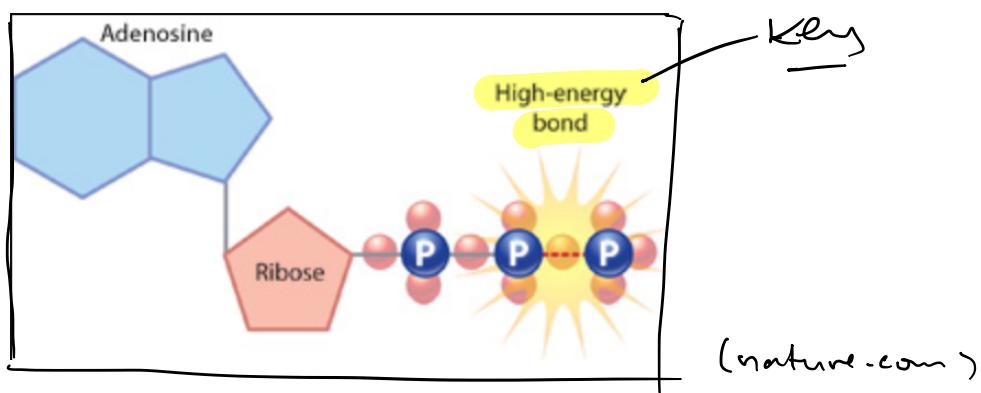
Answer: _____

ATP: The energy currency of the cell

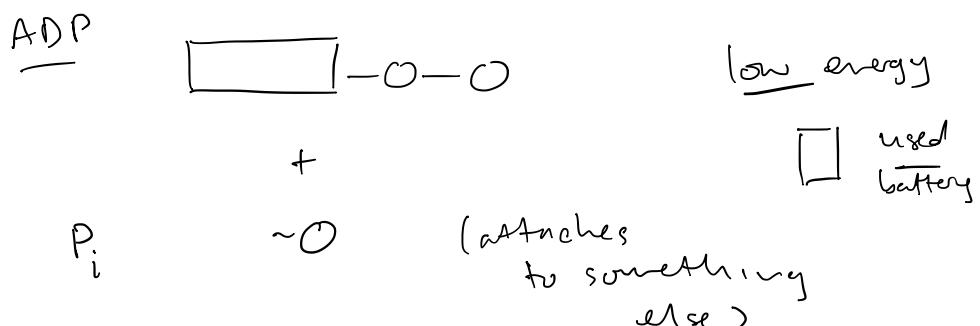
Big Picture:



ATP: molecular 'battery'



↓
break bond =>
release energy

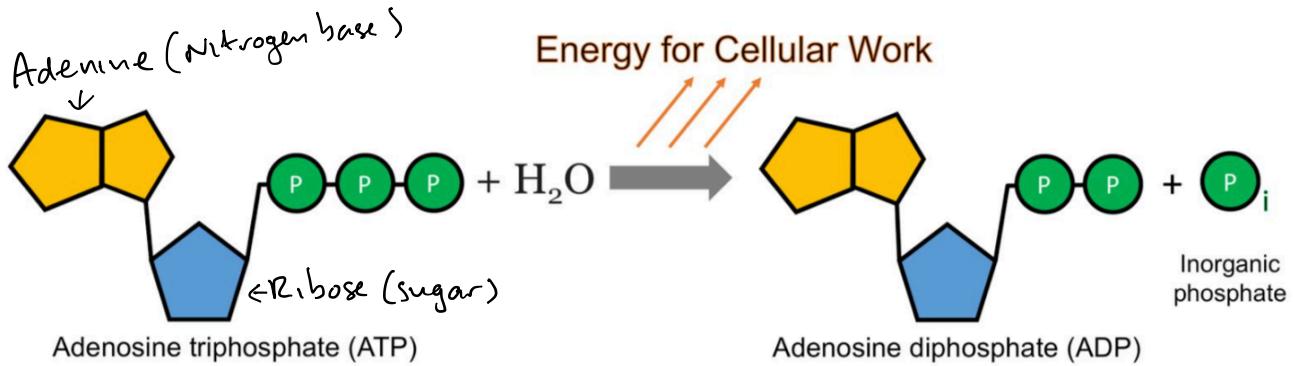


ATP structure & Hydrolysis

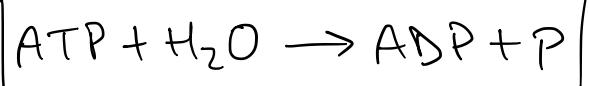
A : adenosine

TP: triphosphate (3 phosphate)

DP: diphosphate (2 phosphate)



Hydrolysis of ATP
/ water splitting



Key reaction!

• $\Delta G = -29 \text{ kJ/mol}$ ($\Delta G < 0 !$)

- couple this reaction (e.g. by transferring the phosphate group to another molecule)

↳ 'energises' the other molecule

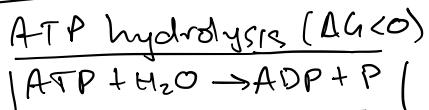
↳ adding phosphate group is called:

phosphorylation

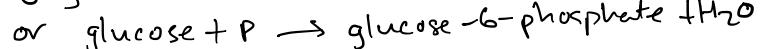
↳ might be energising a 'helper'/intermediate molecule/protein rather than the target directly

ATP Coupling

T fructose & glucose: monosaccharides
S sucrose: disaccharide

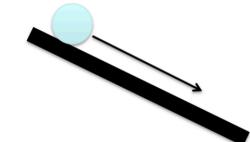


Something else! ($\Delta G > 0$)

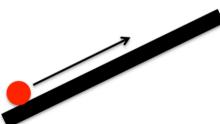


i phosphorylation

Couple together

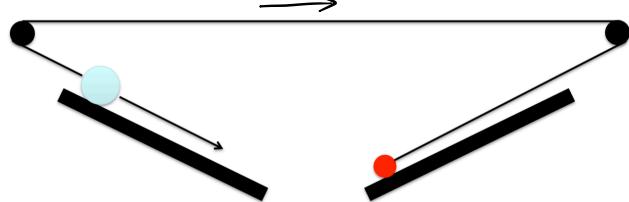


'favourable reaction'



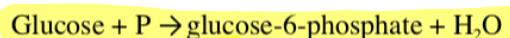
'unfavourable reaction'

Coupling: transfer phosphate P_i (directly to target or to helper molecule)



overall favourable ($\Delta G < 0$)

- 39) The phosphorylation of glucose is the initial step in the catabolism of glucose in the cell.



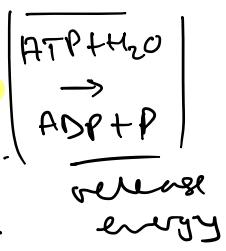
$$\Delta G = 13.8 \text{ kJ/mol}$$

- a. Explain why this reaction does not take place spontaneously. (1 mark)

Answer: $\Delta G > 0$ (Spontaneous: $\Delta G < 0$ at constant T, P)

- b. In the cell, the reaction is coupled to the hydrolysis of ATP. Explain how coupling the reaction to ATP hydrolysis enables the phosphorylation of glucose to take place in the cell. (1 mark)

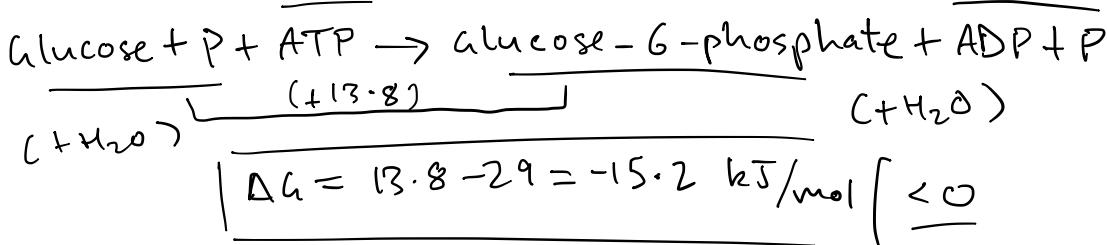
Answer: Hydrolysis of ATP is energetically favourable/spontaneous ($\Delta G < 0$) & sufficient to make overall $\Delta G = \Delta G_{\text{Phos}} + \Delta G_{\text{Hyd.}} < 0$ (see below).



- c. Write down the coupled reaction and calculate the free energy change for the coupled reaction under standard conditions. The free energy of hydrolysis of ATP is -29 kJ/mol under standard conditions. (2 marks)

Answer:

(-29)



(or glucose + ATP \rightarrow glucose-6-phosphate + ADP, cancelling P_i)

Same idea for many processes :

- phosphorylates molecules (transfers P from ATP)
& 'energises' them (with some loss)
- These molecules can in turn 'release' P (de-phosphorylate)
(or transfer) & hence do work/transfer energy in process

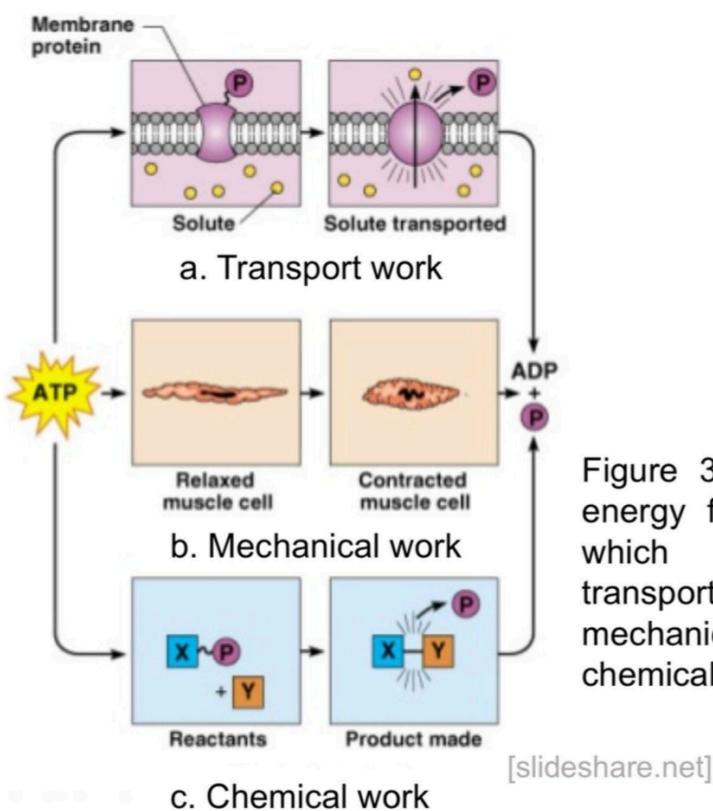


Figure 31: ATP releases energy for cellular work, which includes (a) transport work, (b) mechanical work, and (c) chemical work

→ [work] →
phosphorylate dephosphorylate
(add P to release P from
molecule, protein molecule, protein
etc) etc).

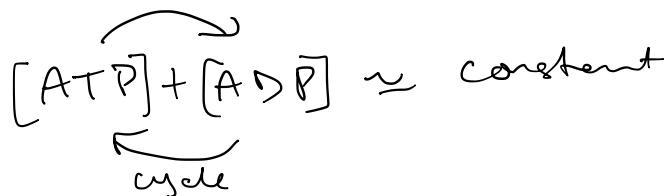
ATP cycle

Cells are constantly using ATP

→ Eg: working muscle cell $\sim 10 \times 10^6$ ATP molecules/second!

→ majority is not made from scratch

→ instead, it is generated from ADP
by re-phosphorylation



→ making new ATP (from ADP etc)
requires energy input of course!

→ Process of Food \rightarrow ATP is
cellular respiration

(next lecture).

Example.

The total quantity of ATP in the human body is about 0.1 mole. The average human recycles 100-150 moles of ATP daily. What does this tell us about the number of times each ATP molecule is recycled during a single day?

$$\sim \frac{100-150 \text{ moles}}{0.1 \text{ mol/cycle}} / \text{day} \approx 1000-1500 \text{ cycles/day}$$

(we use 0.1 mol =
1 full usage of store
available.)

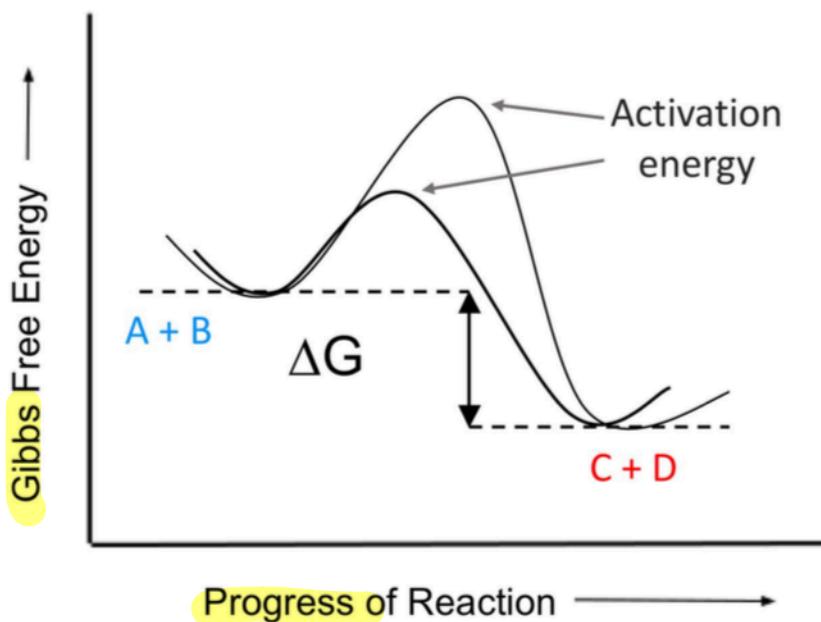
Chemical kinetics

o Thermodynamics : [what is possible] /
 → NOT : how or how fast



→ need 'constitutive' models of
 specific mechanisms etc

o Kinetics : [how & how fast]



Two reactions

- Same ΔG
- different rates

Figure 32: Although ΔG informs us of whether or not the reaction will be spontaneous or not, it tells us nothing of the rate of reaction. The two reactions illustrated here have the same ΔG , but different reaction rates and activation energies.

Rate of reaction

Rate of a reaction : rate at which product is formed

$$\boxed{\text{Rate} = \frac{\Delta \text{amount}}{\Delta \text{time}}}$$

e.g. $\frac{1}{\text{Vol}} \cdot \frac{\Delta n}{\Delta t} [=] \text{mol.m}^{-3} \cdot \text{s}^{-1}$

$$(\Delta \text{conc.}/\Delta \text{time})$$

Eg.

What is the rate of consumption of hydrogen gas in the following reaction when its concentration decreases by 0.2 mol/L in 10 s ? $H_2 + I_2 \rightarrow 2 HI$

Is the rate the same if expressed in terms of HI ?

$$\text{rate of consumption} : (0.2 \text{ mol/L}) \left(\frac{1}{10 \text{ s}} \right) = 0.02 \text{ mol H}_2 / \text{L.s}$$

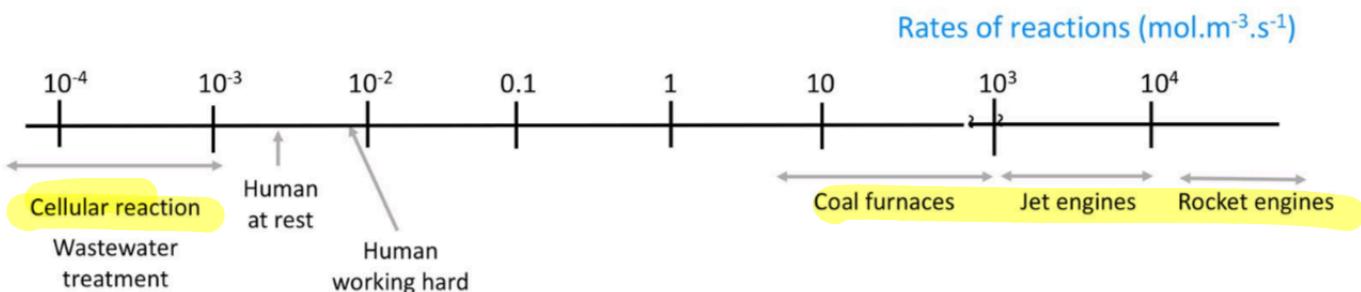
$$\begin{aligned} \text{rate of production} &= \text{reaction rate} = 2 \times \text{consumption rate} \\ &= 0.04 \text{ mol HI/L.s} \end{aligned}$$

Biological reactions

(cf eq combustion & similar)

are

- slow (naturally)
- efficient
- highly controlled



Effect of temperature (on general reactions)

Collision theory: a reaction requires high energy collisions to break bonds

So:

Higher temp. \Rightarrow more high-energy \Rightarrow faster reaction

we

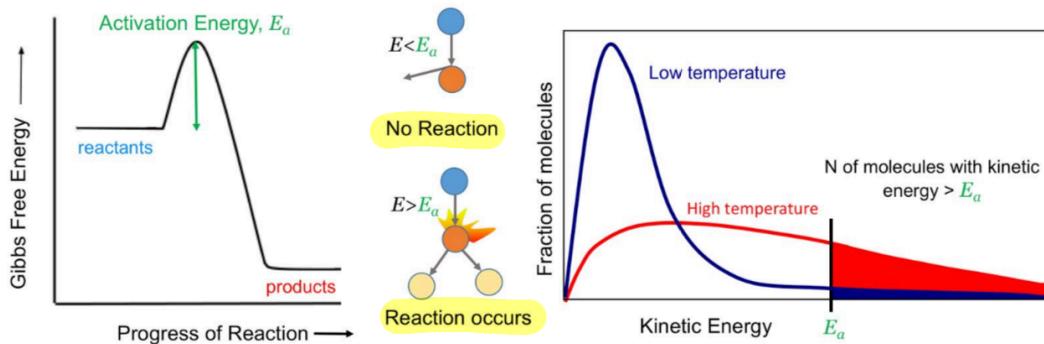


Figure 33: For a chemical reaction to occur, molecules must collide. These collisions must have enough energy to break the bonds of the reactants. This energy barrier is called the Activation Energy, E_a . When a collision has the energy equal or greater than the activation energy, a reaction can occur. At higher temperatures there are a greater number of molecules with kinetic energy $> E_a$, thus increasing the likelihood of a reaction.

Speed up?

Issue: body temp. is stable $\approx 37^\circ\text{C}$!

\rightarrow can't boil cells!

Solution: enzyme

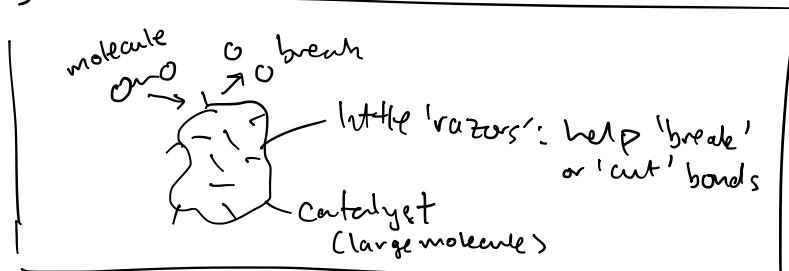
\rightarrow biological catalyst

Catalysts & Enzymes

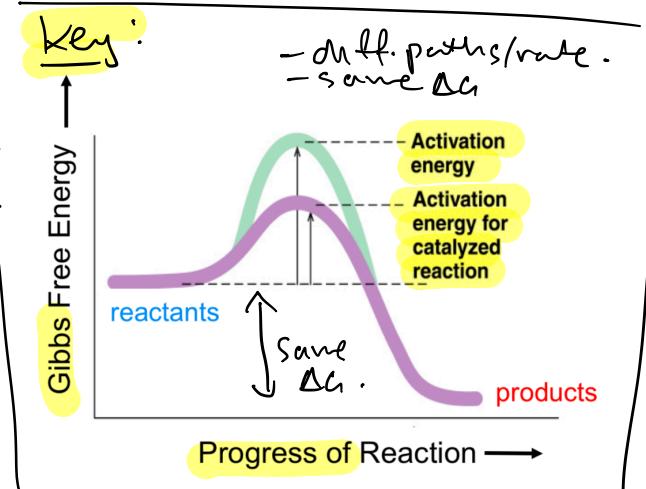
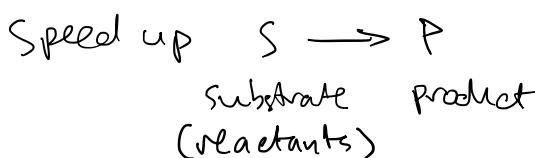
Catalyst: molecule that speeds up a reaction, without being consumed itself

→ lowers the activation energy

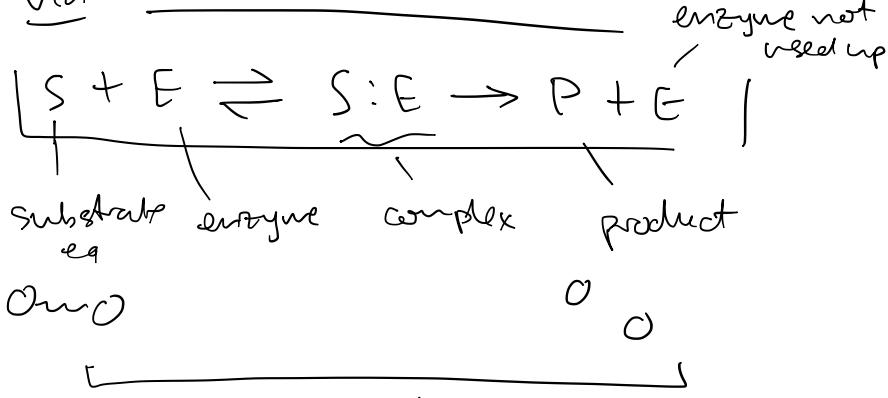
e.g.



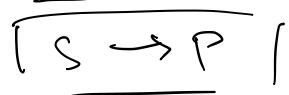
Enzyme: Biological catalyst



Via



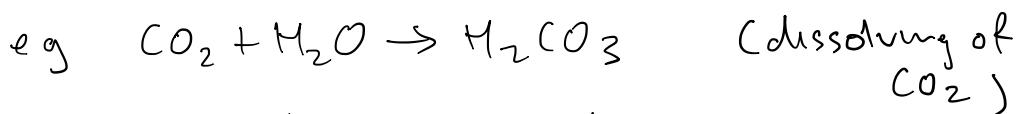
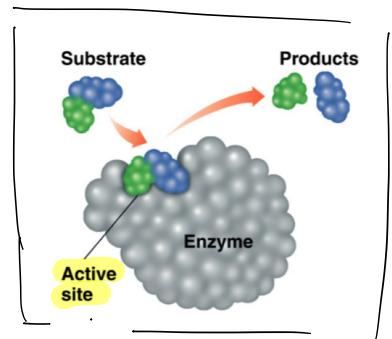
Overall still



- Same ΔG (same overall result)
- Faster

Enzymes

- Nearly all cellular reactions are catalysed by enzymes
 - speed, control & efficiency



→ naturally very slow

→ in body, is catalysed by carbonic anhydrase (speed up $\sim 10^7$)

↳ key indicator of enzyme (-ase)

- Typically increase rates by factor $\sim 10^6 - 10^7$!

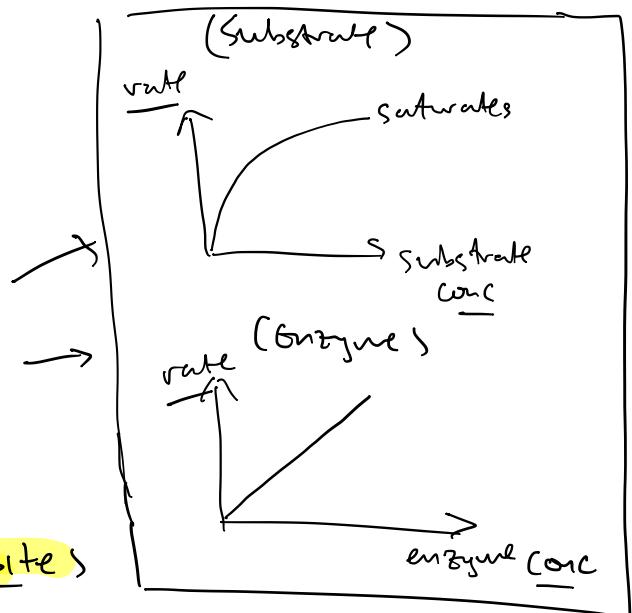
- Are proteins with shape/structure tailored to specific reactions

Enzyme activity affected by

- Temperature (best at body temp)
- pH (usually 7.4 but can vary)
- substrate concentration (\uparrow)
- enzyme concentration (\uparrow)
- enzyme inhibition (\downarrow)

↳ competitive (bind to active sites)

↳ non-competitive (bind to another site)



Examples

2017 Exam

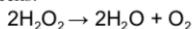
40) Which of the following statements about the molecule adenosine triphosphate (ATP) are FALSE? (1 mark)

- W. ATP drives cellular work by transferring a phosphate group to a recipient molecule.
 X. Almost 100% of the chemical energy in food molecules is converted into ATP to carry out cellular work.
 Y. When an ATP molecule is used for cellular work, the remaining ADP and phosphate can be recycled to make another ATP.
 Z. The generation of energy-rich ATP molecules during cellular respiration relies on producers harnessing light energy during photosynthesis.

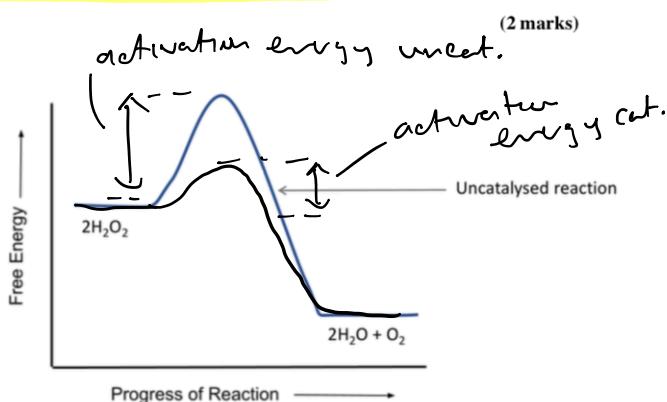
- A. W only
 B. Y and Z
 C. X and Z
 D. X only
 E. W and X

Answer: C

41) Enzymes are biological catalysts. The enzyme 'catalase' catalyses the following reaction of H_2O_2 (hydrogen peroxide) in cells:



- a. The reaction coordinate diagram below shows the uncatalysed breakdown of hydrogen peroxide to water and oxygen. Draw in the curve for the catalysed reaction and label the activation energy for both the catalysed and uncatalysed reactions. (2 marks)



- b. Various factors affect the activity of enzymes. Explain how surrounding temperatures of 20 °C, 37 °C and 50 °C would affect the activity of catalase. (2 marks)

Answer: 20°C ↓, 37°C good, 50°C ↓
not enough; body temp; 'denature' (or cook!)
energy

course book

The average rate of combustion of a candle made of paraffin, $\text{C}_{25}\text{H}_{52}$, is $8.33 \times 10^{-4} \text{ mol/min}$. The molar mass of paraffin is 352.6 g/mol. You want the candle to burn for 4h. The candle is only sold in four sizes: 25, 50, 75 or 100 g. Which one is the smallest one you could use?

$$\text{Burn rate} = 8.33 \times 10^{-4} \text{ mol/min} \quad (\Delta \text{amount} / \Delta \text{time})$$

$$\text{Required time} = 4\text{h} = 4 \times 60 = 240 \text{ min}$$

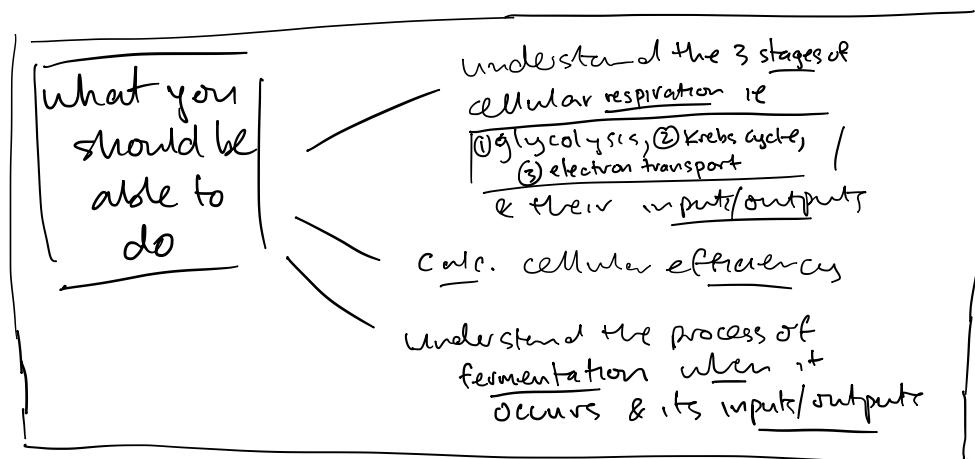
$$\begin{aligned} \text{Amount required} &= 8.33 \times 10^{-4} \text{ mol/min} \times 240 \text{ min} \\ &\approx 0.2 \text{ mol} = 0.2 \text{ mol} \times 352.6 \text{ g/mol} \\ &\approx 70.5 \text{ g} \Rightarrow \text{smallest meeting this req.} \\ &\text{is } \underline{\underline{75 \text{ g}}} \end{aligned}$$

Lecture 16

(7.8, 7.9, 7.10 in course books)

Topics

cellular respiration
cellular efficiency
Fermentation



Examples

42) Which of the following TWO statements about respiration are TRUE?

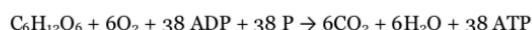
(1 mark)

- W. Oxygen gas is reduced during cellular respiration.
 - X. Fermenting yeast cells produce lactic acid during bread making.
 - Y. The Krebs Cycle produces citric acid.
 - Z. Glycolysis requires an initial input of energy to split glucose.
- A. W and Z
B. X and Y
C. W and X
D. Y and Z

Answer: _____

respiration &
efficiency

43) The free energy available from glucose is $\Delta G = -2862 \text{ kJ/mol}$ under standard conditions. In respiration, ATP molecules are synthesised for each glucose molecule, as follows:



Under standard conditions, each ATP can contribute $\Delta G = -29 \text{ kJ/mol}$ to drive reactions in the cell. What is the efficiency of the cell?

(1 mark)

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: _____

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:

fermentation.

Cellular respiration:



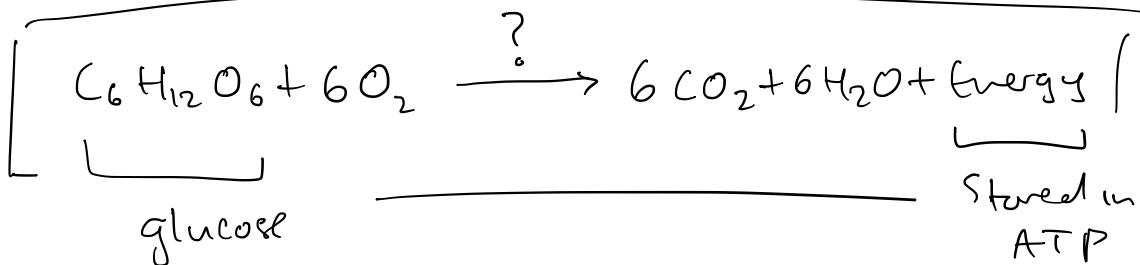
Via a metabolic pathway consisting of a series of enzyme catalysed reactions

metabolism - all reactions involved in maintaining living state

↳ catabolism: breakdown of molecules for energy

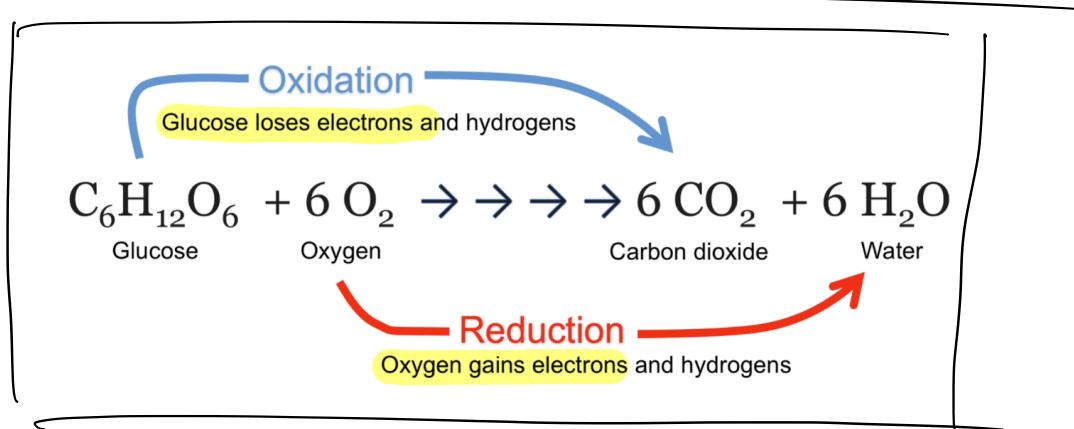
↳ anabolism: synthesis of useful molecules

Overall: (we focus on glucose here - others too though!)



Redox reactions: (reduction-oxidation)

- transfer of electrons
 - OIL - RIG
- Oxidation Reduction
 is losing is gaining
 electrons electrons



→ Glucose is oxidised (loses electrons & hydrogen)

→ Oxygen is reduced (accepts electrons & hydrogen)

Key stages (steps) of cellular respiration

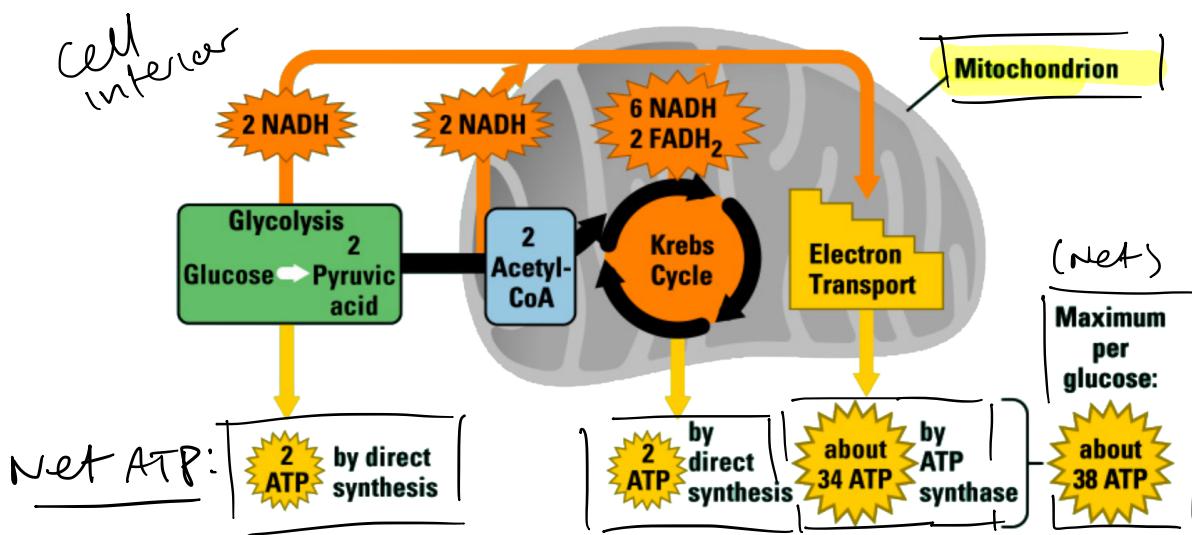
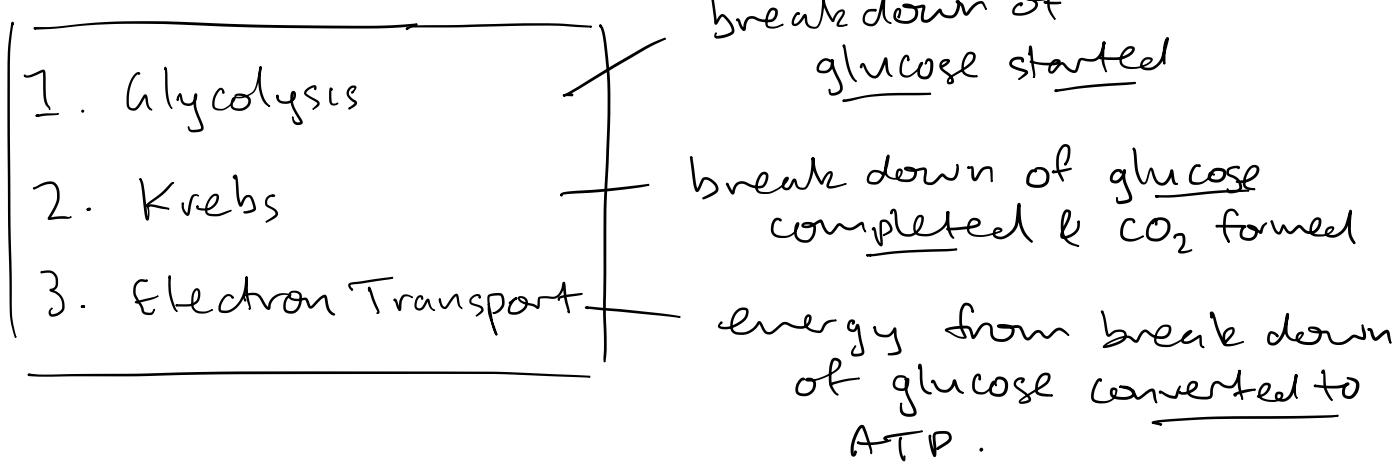


Figure 40: During cellular respiration, 1 molecule of glucose creates ~38 molecules of ATP. One cell can have 1000 to 2000 mitochondria producing many energy-rich ATP molecules

NAD & FAD?

Key:

- loading up in 1 & 2
- unloading in 3.

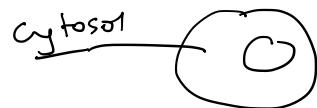
→ electron "shuttles" (unloaded forms)

→ NADH & FADH₂ are "loaded up" forms

→ unload in final stage to get energy!

I. Glycolysis

(lysis = splitting)

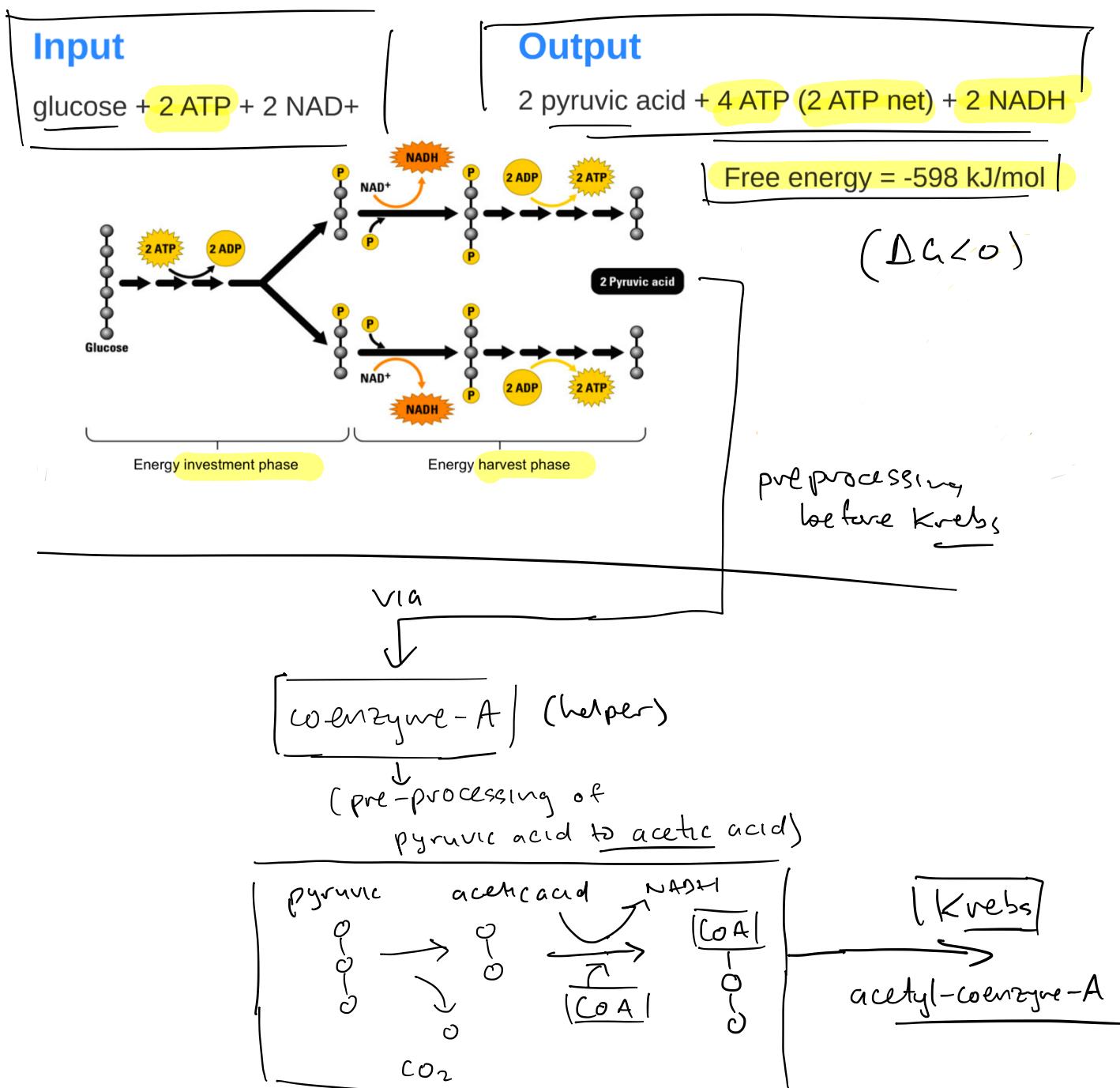


- Series of 9 reactions in cytosol of cell that begins the break down of glucose

(~100 years to discover & elaborate full pathway!)

- Key: Investment: 2 ATP
Output : 4 ATP } 2 ATP net + 2 NADH
(loaded 'buses')

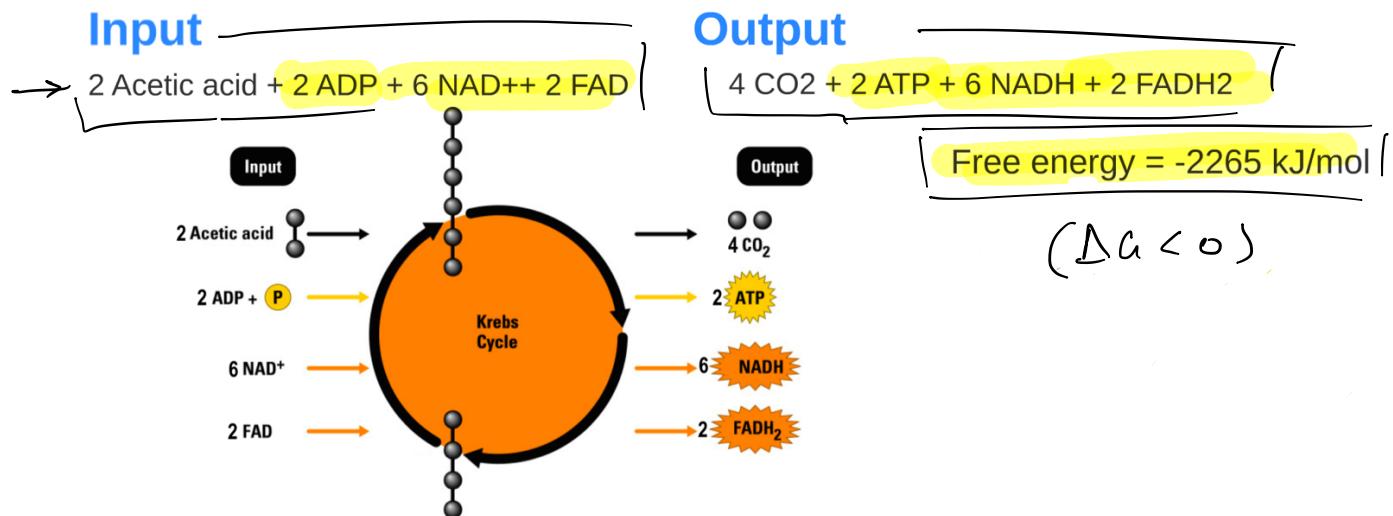
Initial 'splitting' of glucose, involving a series of 9 reactions



2. Krebs

From glycolysis (via co-enzyme-A) ... to Krebs's

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



- Key: { 2 ATP by direct synthesis
 { 6 NADH + 2 FADH₂ 'loaded buses'
 (of electrons),

→ Also known as: citric acid cycle (no net production of citric acid)

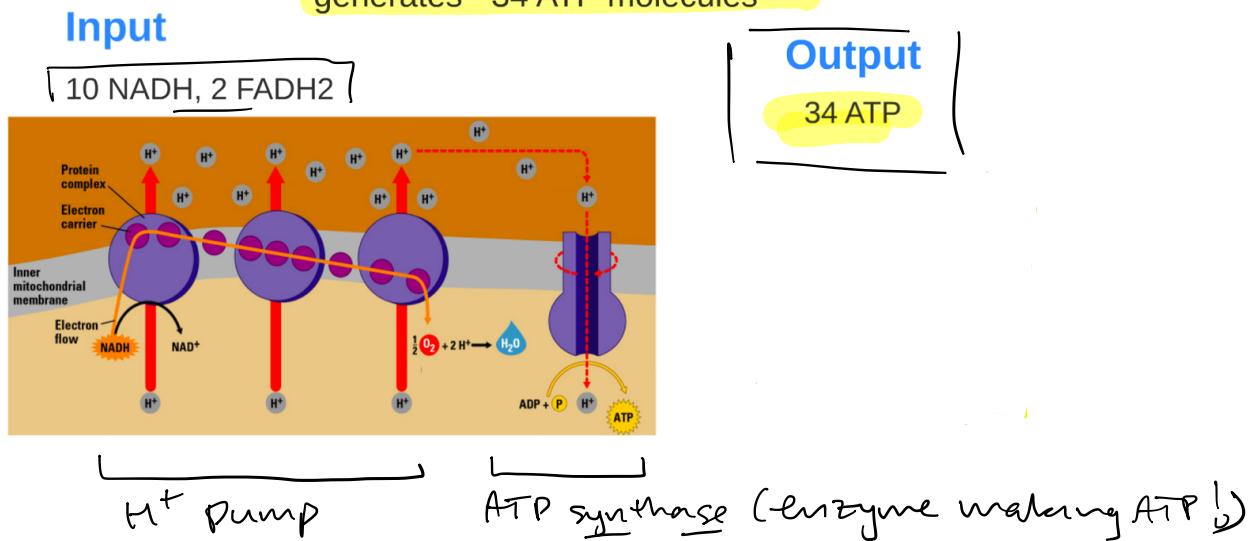
The name of this metabolic pathway is derived from the **citric acid** (a type of tricarboxylic acid, often called citrate, as the ionized form predominates at biological pH^[5]) that is consumed and then regenerated by this sequence of reactions to complete the cycle. The cycle consumes acetate (in the form of **acetyl-CoA**) and **water**, reduces **NAD⁺** to **NADH**, and produces carbon dioxide as a waste byproduct. The NADH generated by the citric acid cycle is fed into the **oxidative phosphorylation** (electron transport) pathway. The net result of these two closely linked pathways is the oxidation of nutrients to produce usable chemical energy in the form of ATP.

(w1k1)

3. Electron Transport

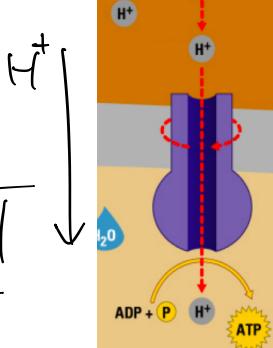
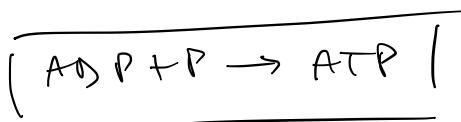
- “unloaded the buses” (NADH & FADH₂)

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



- electrons ‘unloaded’ (hence redox reaction)
- used to pump protons (hydrogen ions) across inner mitochondrial membrane
- this H^+ gradient is then used to ‘power’ the ATPase enzyme which phosphorylates ADP to ATP.

ie



Summary

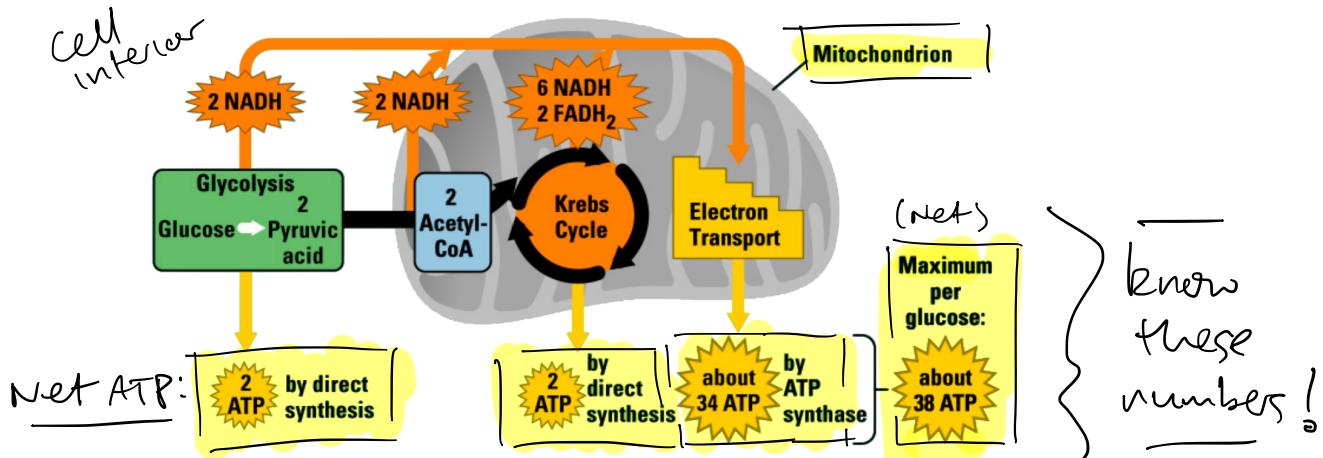


Figure 40: During cellular respiration, 1 molecule of glucose creates ~38 molecules of ATP. One cell can have 1000 to 2000 mitochondria producing many energy-rich ATP molecules

Efficiency

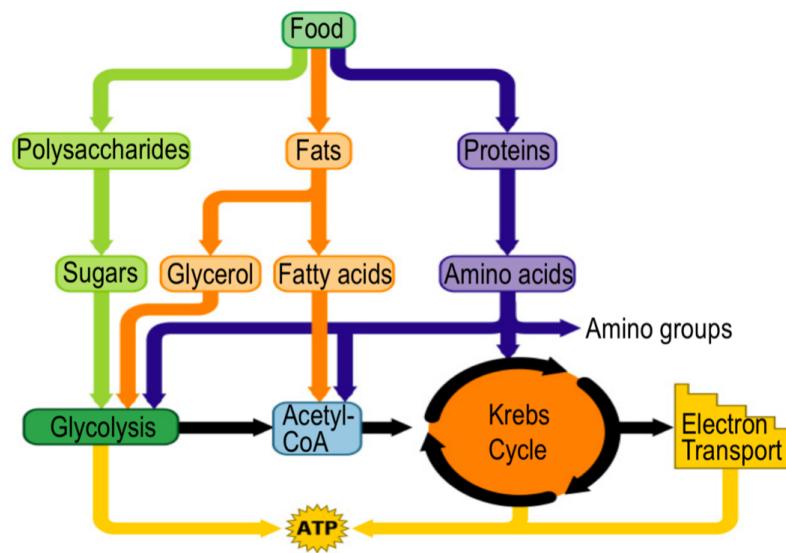
- Free energy available from glucose $\Delta G = -2862 \text{ kJ/mol}$
- Cellular respiration: 38 ATP/glucose molecule.
- Free energy available from ATP: $\Delta G = -29 \text{ kJ/mol}$

$$\Rightarrow \left| \begin{array}{l} \text{Efficiency} = \frac{\text{Output}}{\text{Input}} = \frac{38 \text{ ATP} \times (-29 \text{ kJ/mol})}{-2862 \text{ kJ/mol}} \\ \approx 38.5\% \end{array} \right|$$

Just glucose?

No !

Cellular respiration can use many different food molecules to generate ATP



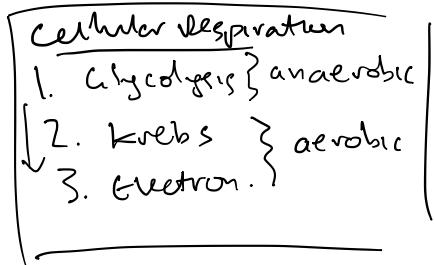
Just Respiration? No!

Fermentation

- Parts of cellular respiration require oxygen → is aerobic
 - What if not available?
 - Can also generate ATP without oxygen present!
 - (anaerobic conditions)
- } fermentation

Stage 1 of cellular respiration
doesn't require oxygen →

⇒ glycolysis can be used
to generate (some) ATP { **key**



But

⇒ only 2 ATP (cf 38 ATP)!

⇒ NADH produced but can't be oxidised in usual way
(by O₂ during electron transport)

↳ Instead, use NADH produced to reduce
the pyruvic acid to

{ lactic acid (human muscles)
ethanol & CO₂ (yeast)

↳ allows glycolysis to continue

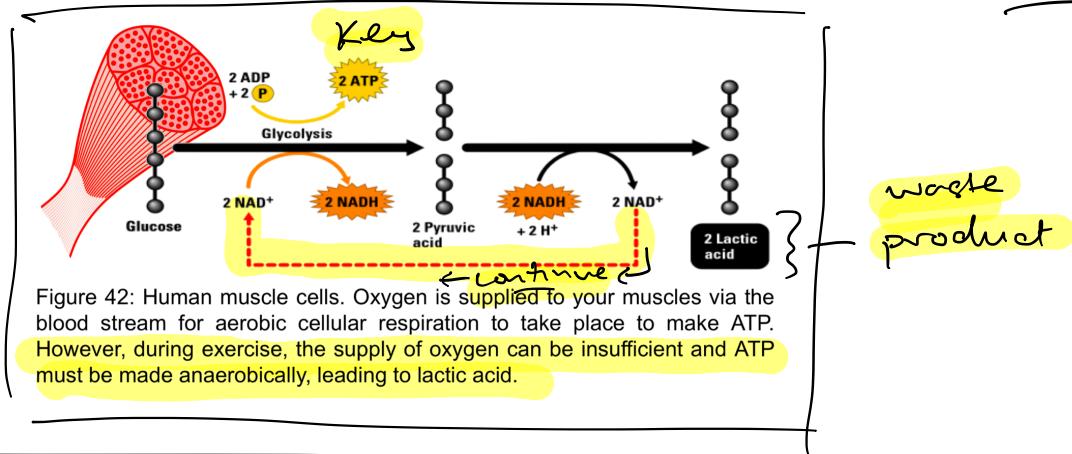
→
e Kample S

Fermentation

- Human muscle cells (during intense exercise
→ not enough O₂)

Fermentation produces lactic acid:

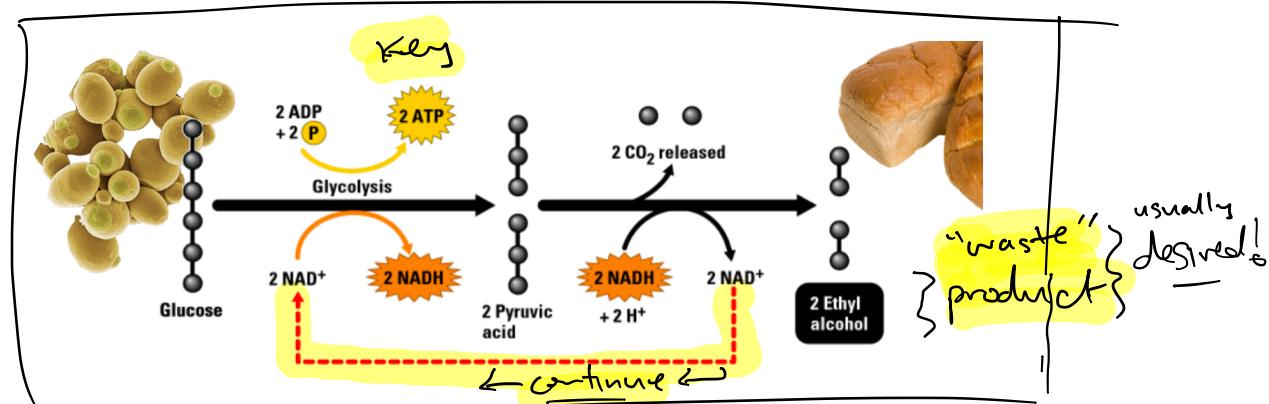
Note: not cause of burning sensation! (Actually tends to counteract)



- Micro-organisms/bacteria (eg yeast)

→ can perform both {respiration
fermentation}

Fermentation producing ethanol & CO₂



- Industrial fermentation (bulk growth of micro organisms producing useful by-products)
 - biofuels
 - antibiotics
 - feed stock etc

Examples

42) Which of the following TWO statements about respiration are TRUE?

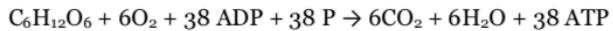
(1 mark)

- ✓ W. Oxygen gas is reduced during cellular respiration.
- ✗ X. Fermenting yeast cells produce lactic acid during bread making.
- ✗ Y. The Krebs Cycle produces citric acid. (not yet)
- ✓ Z. Glycolysis requires an initial input of energy to split glucose.

- A. W and Z
- B. X and Y
- C. W and X
- D. Y and Z

Answer: A

43) The free energy available from glucose is $\Delta G = -2862 \text{ kJ/mol}$ under standard conditions. In respiration, ATP molecules are synthesised for each glucose molecule, as follows:



Under standard conditions, each ATP can contribute $\Delta G = -29 \text{ kJ/mol}$ to drive reactions in the cell. What is the efficiency of the cell?

(1 mark)

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 FADH₂ are passed from molecule to molecule in the electron transport chain in a series of redox reactions

Answer: B

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:

only get 2 ATP under anaerobic fermentation
(compared to 38 under aerobic respiration)