Lectures 15/16 (Energy). EngGen140

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)

Topics
- ATP as energy currency of cell
- 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

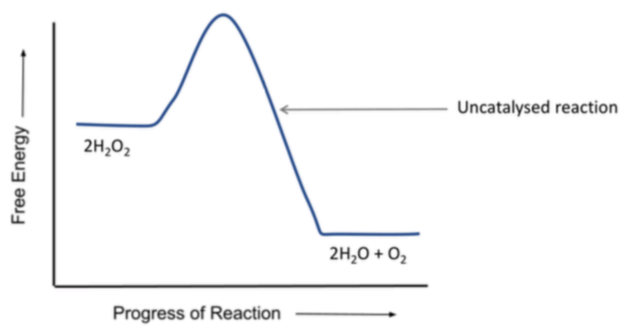
Answer: ______________

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

$$2H_2O_2 \rightarrow 2H_2O + O_2$$

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:

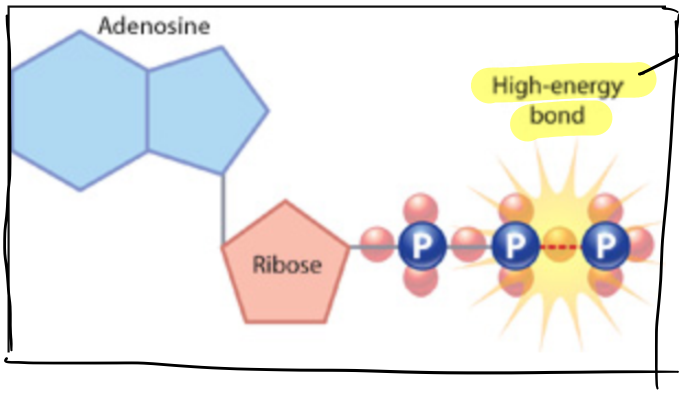
ATP: The energy currency of the cell

Big picture:

Food/Light → ATP → useful processes

'Bank'/store energy — 'spend'/use energy

ATP: molecular 'battery'



Key

(nature.com)

ATP ▭–O–O~O High energy — charged battery

↓ break bond ⇒ release energy

ADP ▭–O–O low energy — used battery

+

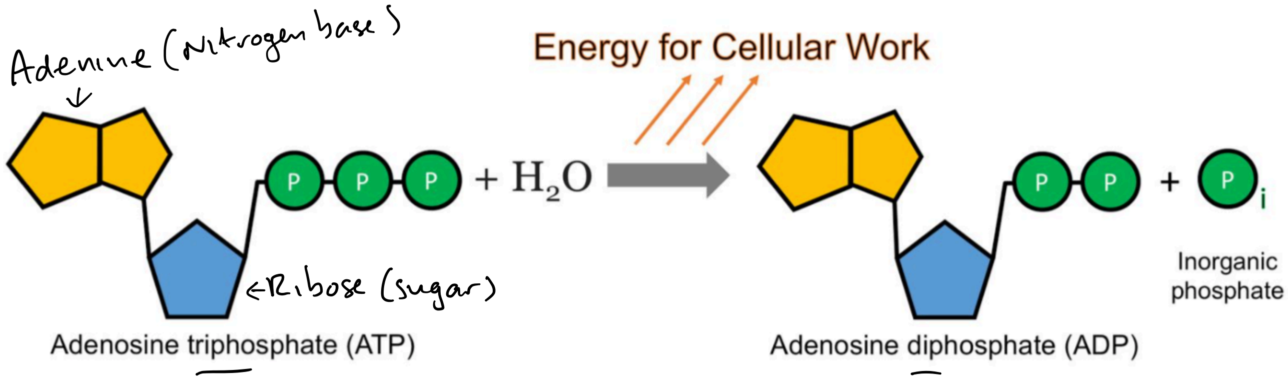
P_i ~O (attaches to something else)

ATP structure & Hydrolysis

A : adenosine

TP : tri phosphate (3 phosphate)

DP : di phosphate (2 phosphate)



Hydrolysis of ATP

water — splitting

$$\boxed{ATP + H_2O \rightarrow ADP + P}$$

Key reaction!

- $\Delta G = -29\ kJ/mol$ ($\Delta G < 0$!)
- couple this reaction (eg by transferring the phosphate group to another molecule)
  - ↳ 'energises' the other molecule
  - ↳ adding phosphate group is called:

$\boxed{\text{phosphorylation}}$

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

glucose & fructose: monosaccharides
sucrose: disaccharides

ATP coupling

ATP hydrolysis ($\Delta G<0$)

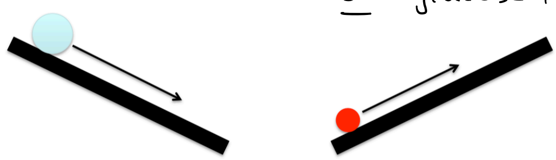
$\boxed{ATP + H_2O \rightarrow ADP + P}$

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

eg glucose + fructose $\rightarrow$ sucrose + H_2O

or glucose + P $\rightarrow$ glucose-6-phosphate + H_2O

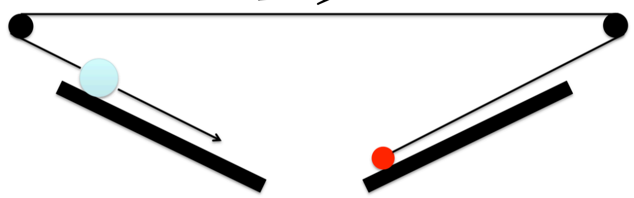
phosphorylation



'favourable reaction' 'unfavourable reaction'

couple together

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



overall favourable ($\Delta G<0$)

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

Glucose + P $\rightarrow$ glucose-6-phosphate + H_2O
$\Delta G = 13.8$ 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)**

$\boxed{ATP + H_2O \rightarrow ADP + P}$

release energy

Answer: Hydrolysis of ATP is energetically favourable/spon. ($\Delta G<0$) & sufficient to make overall $\Delta G = \Delta G^{phos} + \Delta G^{hyd.} < 0$ (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:

$$\text{Glucose} + \underbrace{P + \overbrace{ATP \rightarrow \text{glucose-6-phosphate}}_{(+13.8)} + ADP + P}^{(-29)}$$

(+ H_2O) (+ H_2O)

$$\boxed{\Delta G = 13.8 - 29 = -15.2 \text{ kJ/mol}} < 0$$

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

Same idea for many processes:

→ phosphorylates molecules (transfers P from ATP) & 'energises' them (with some loss)

→ These molecules can in turn 'release' P (de-phosphylate) (or transfer) & hence do work/transfer energy in process

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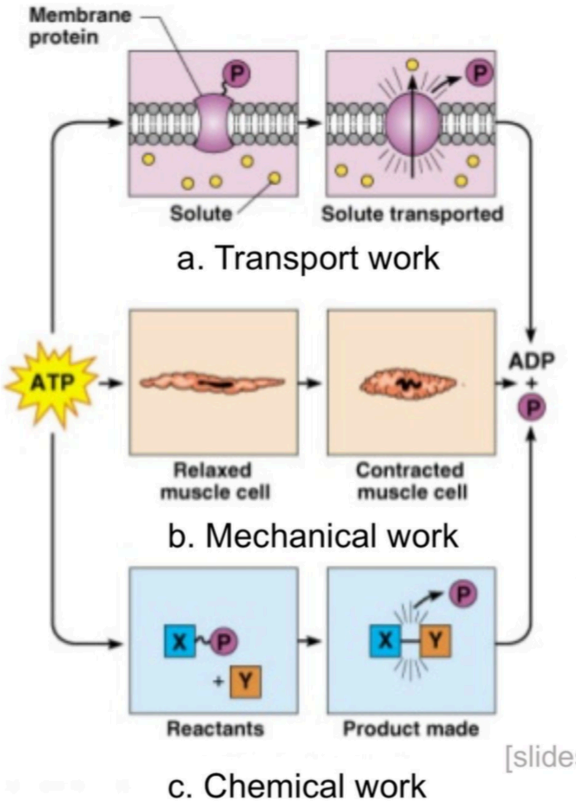


Figure 31: ATP releases energy for cellular work, which includes (a) transport work, (b) mechanical work, and (c) chemical work

[slideshare.net]

→ [work] →

phosphorylate (add P to molecule, protein etc)

dephosphorylate (release P from molecule, protein etc).

ATP cycle

Cells are constantly using ATP

→ Eg: working muscle cell ~ 10×10^6 ATP molecules/second!

→ majority is not made from scratch

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

$$[ATP] + [ADP] \simeq \text{constant}$$

cycle

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

→ Process of Food → ATP is

| cellular respiration |

(next lecture).

Example.

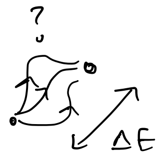
The total quantity of ATP in the human body is about 0.1 mole. The average human recycles 100-150 moles of ATP daily. What does this tell us about the number of times each ATP molecule is recycled during a single day?

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

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

Chemical kinetics

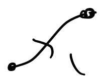
- Thermodynamics : | what is possible |



  → NOT : how or how fast

  → need 'constitutive' models of specific mechanisms etc

- Kinetics : | how & how fast |



specific path

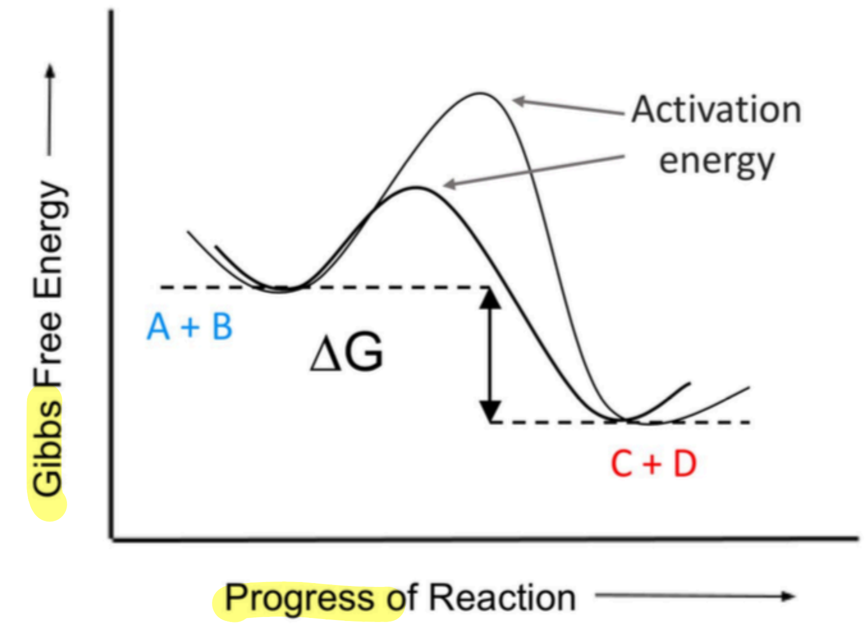


Figure 32: Although ΔG informs us of whether or not the reaction will be spontaneous or not, it tells us nothing of the rate of reaction. The two reactions illustrated here have the same ΔG, but different reaction rates and activation energies.

Two reactions

- same ΔG
- different rates

Rate of reaction

Rate of a reaction : rate at which |product| is formed

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

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

(Δconc./Δtime)

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?

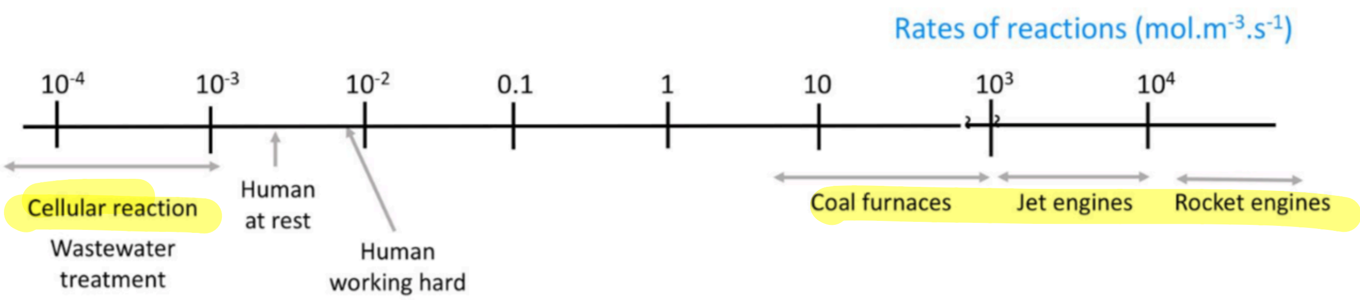
rate of consumption : $(0.2\ mol/L)\left(\frac{1}{10\ s}\right) = 0.02\ mol\ H_2/L.s$

rate of production = reaction rate = 2 x consumption rate
$= 0.04\ mol\ HI/L.s$

Biological reactions

(cf eg 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. => more high energy collisions => faster reaction

re

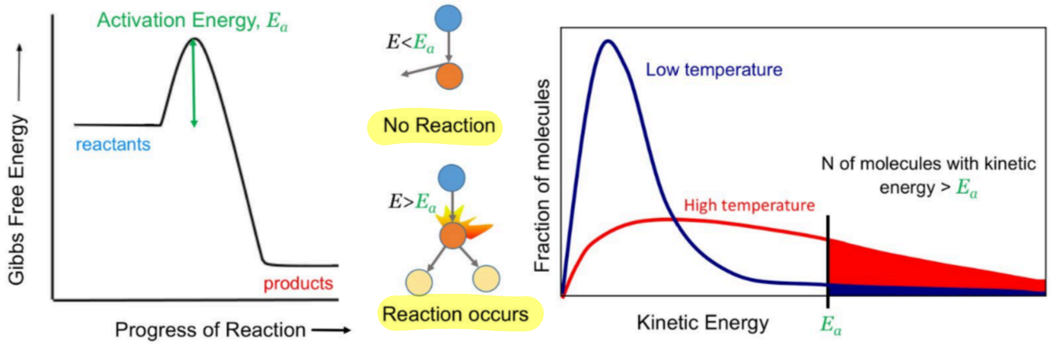


Figure 33: For a chemical reaction to occur, molecules must collide. These collisions must have enough energy to break the bonds of the reactants. This energy barrier is called the Activation Energy, E_a. When a collision has the energy equal or greater than the activation energy, a reaction can occur. 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 ~ 37°C!

→ can't boil cells!

Solution: enzymes

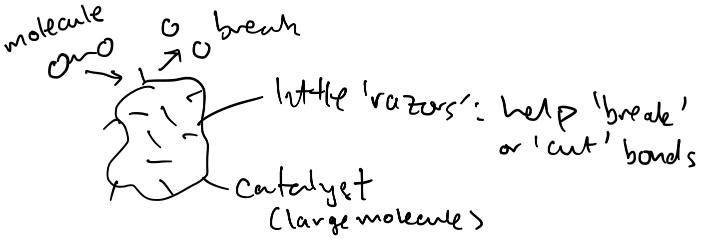
→ biological catalysts

Catalysts & Enzymes

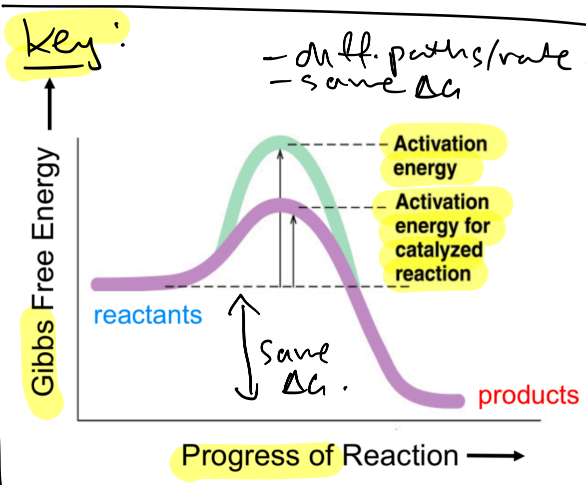
Catalyst: molecule that speeds up a reaction, without being consumed itself

→ lowers the activation energy

eg



- diff. paths/rate.
- same ΔG



Enzyme: Biological catalyst

Speed up $S \rightarrow P$

S: substrate (reactants)

P: product

via

$$S + E \rightleftharpoons S{:}E \rightarrow P + E$$

enzyme not used up

S: substrate, eg O~O

E: enzyme

S:E: complex

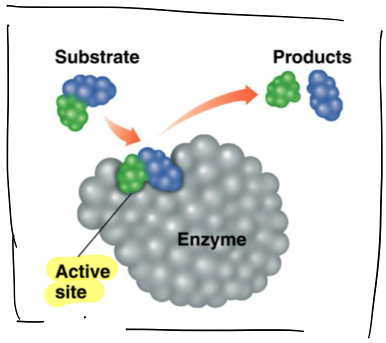
P: product, O O

overall still

$$\boxed{S \rightarrow P}$$

- Same ΔG (same overall result)
- Faster

Enzymes



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

eg $CO_2 + H_2O \rightarrow H_2CO_3$ (dissolving of CO_2)

→ naturally very slow

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

L key indicator of enzyme (-ase)

- Typically increase rates by factor ~ $10^6 - 10^7$!
- Are proteins with shape/structure tailored to specific reactions

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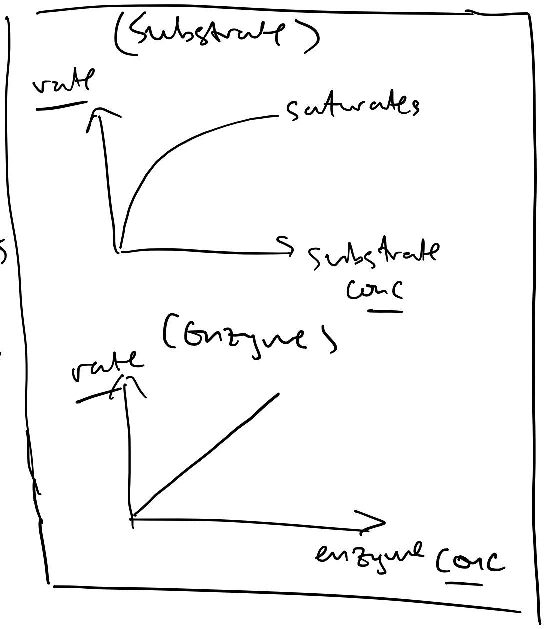
Enzyme activity affected by

- Temperature (best at body temp)
- pH (usually 7.4 but can vary)
- substrate concentration (↑) →
- Enzyme concentration (↑) →
- Enzyme inhibition (↓)

  L competitive (bind to active site)

  L 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:

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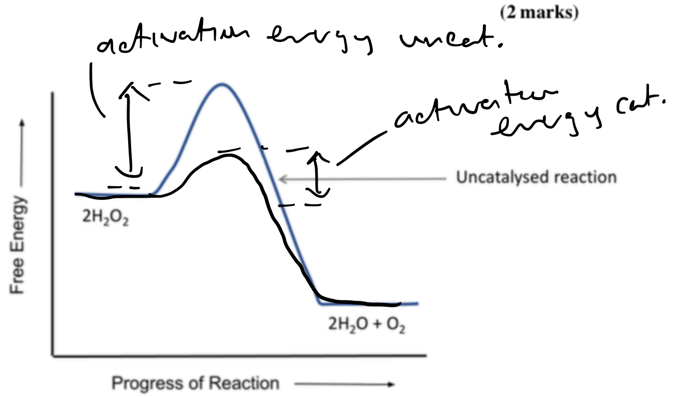
a. The reaction co-ordinate diagram below shows the uncatalysed breakdown of hydrogen peroxide to water and oxygen. Draw in the curve for the catalysed reaction and label the activation energy for both the catalysed and uncatalysed reactions.

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

course book

The average rate of combustion of a candle made of paraffin, $C_{25}H_{52}$, is 8.33 x10^{-4} 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?

Burn rate = 8.33×10^{-4} mol/min (Δ amount / Δ time)

Required time = 4h = 4 × 60 = 240 min

Amount required = 8.33×10^{-4} mol/min × 240 min
≈ 0.2 mol = 0.2 ~~mol~~ × 352.6 g/~~mol~~
≈ 70.2 g ⟹ smallest meeting this req. is $\boxed{75\text{ g}}$

Lecture 16 (7.8, 7.9, 7.10 in course book)

Topics
- cellular respiration
- cellular efficiency
- Fermentation

what you should be able to do
- understand the 3 stages of cellular respiration ie ① glycolysis, ② Krebs cycle, ③ electron transport & their inputs/outputs
- Calc. cellular efficiency
- understand the process of fermentation when it occurs & its inputs/outputs

Examples

respiration & efficiency

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: _______________

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

$$C_6H_{12}O_6 + 6O_2 + 38\ ADP + 38\ P \rightarrow 6CO_2 + 6H_2O + 38\ ATP$$

Under standard conditions, each ATP can contribute $\Delta G = -29$ 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: _______________

fermentation.

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:

Cellular respiration:

Food → ATP

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 of useful molecules

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

$$\underbrace{C_6H_{12}O_6}_{\text{glucose}} + 6O_2 \xrightarrow{?} 6CO_2 + 6H_2O + \underbrace{\text{Energy}}_{\text{Stored in ATP}}$$

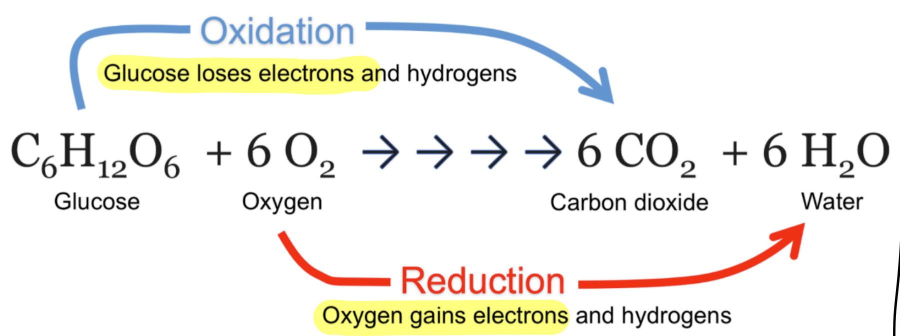
Redox reactions: (reduction – oxidation)

– transfer of electrons

– OIL – RIG

Oxidation is losing electrons

Reduction is gaining electrons



→ Glucose is oxidised (loses electrons & hydrogen)

→ oxygen is reduced (accepts electrons & hydrogen)

Key stages (steps) of cellular respiration

1. Glycolysis — breakdown of glucose started
2. Krebs — breakdown of glucose completed & CO_2 formed
3. Electron Transport — energy from breakdown of glucose converted to ATP.

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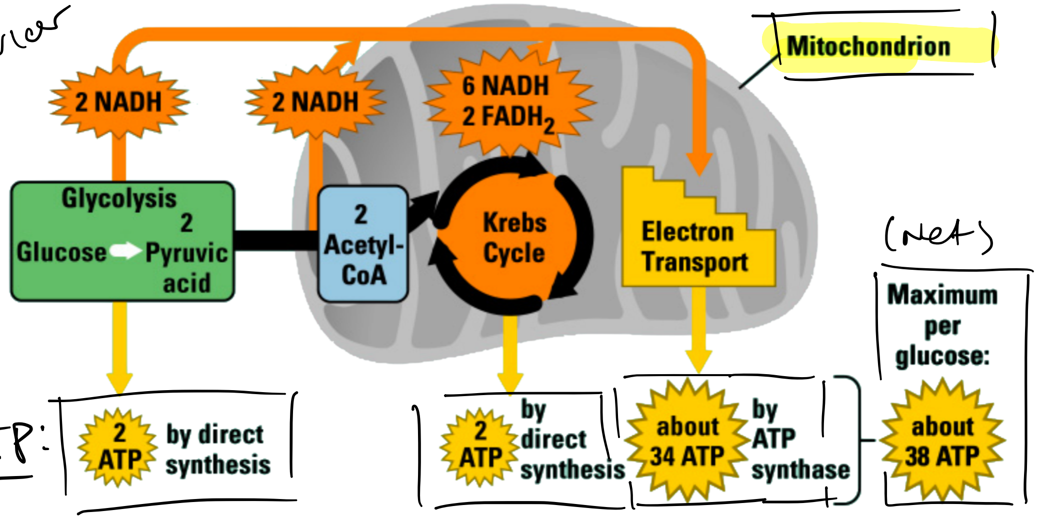
cell interior



Net ATP:

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

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NAD & FAD ?

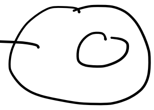
→ electron "shuttles" (unloaded forms)

→ NADH & $FADH_2$ are "loaded up" forms

→ unload in final stage to get energy!

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

1. Glycolysis (lysis = splitting)

cytosol 

- 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 + 2NADH (loaded 'buses')

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

Input

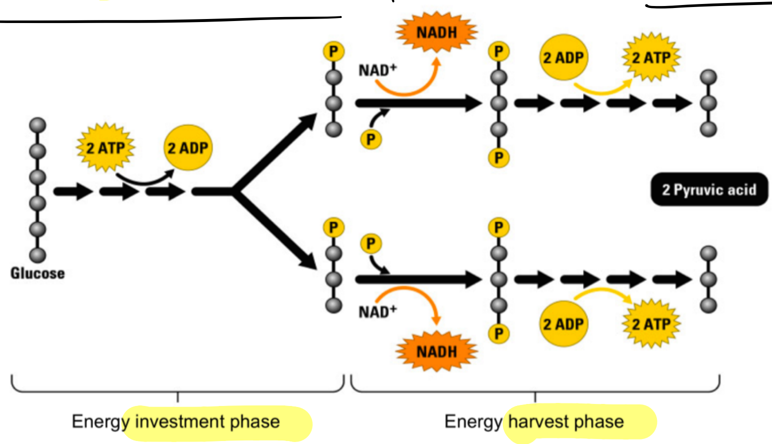
glucose + 2 ATP + 2 NAD+

Output

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

Free energy = -598 kJ/mol

($\Delta G < 0$)



preprocessing before Krebs

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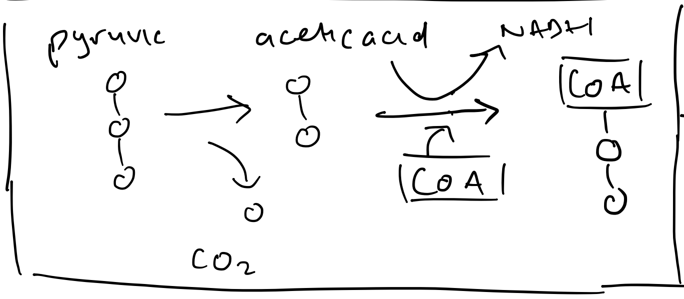
via

coenzyme-A (helper)

(pre-processing of pyruvic acid to acetic acid)



Krebs

acetyl-coenzyme-A

2. Krebs

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

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

Input

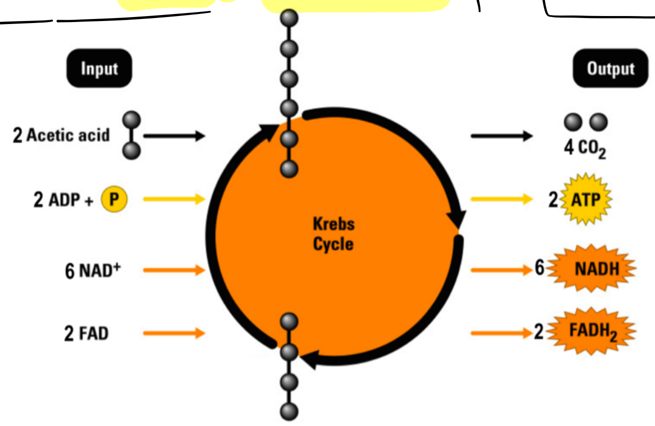
→ 2 Acetic acid + 2 ADP + 6 NAD++ 2 FAD

Output

4 CO2 + 2 ATP + 6 NADH + 2 FADH2

Free energy = -2265 kJ/mol

($\Delta G < 0$)



- Key: 2 ATP by direct synthesis
6NADH + 2FADH$_2$ 'loaded buses' (of electrons).

→ Also known as: citric acid cycle ($C_6H_8O_7$) (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.

(wiki)

3. Electron Transport

- "unload the buses" (NADH & $FADH_2$)

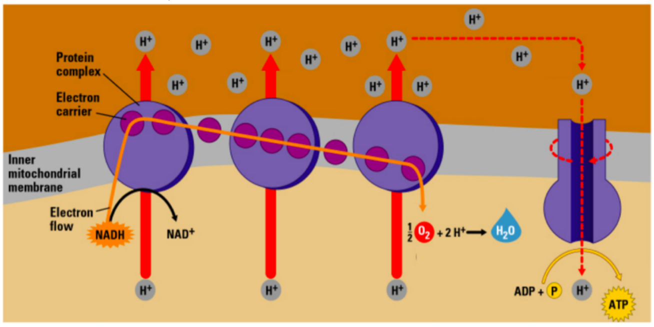
Most of the energy is now in the electrons within the carriers NAD+ and FAD. The **electron transport chain** completes the process of cellular respiration and generates ~34 ATP molecules

Input

10 NADH, 2 FADH2

Output

34 ATP



H^+ pump

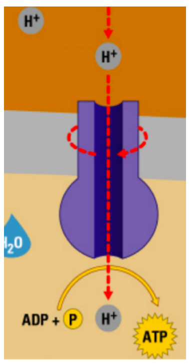
ATP synthase (enzyme making ATP!)

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

ie

$\boxed{ADP + P \rightarrow ATP}$

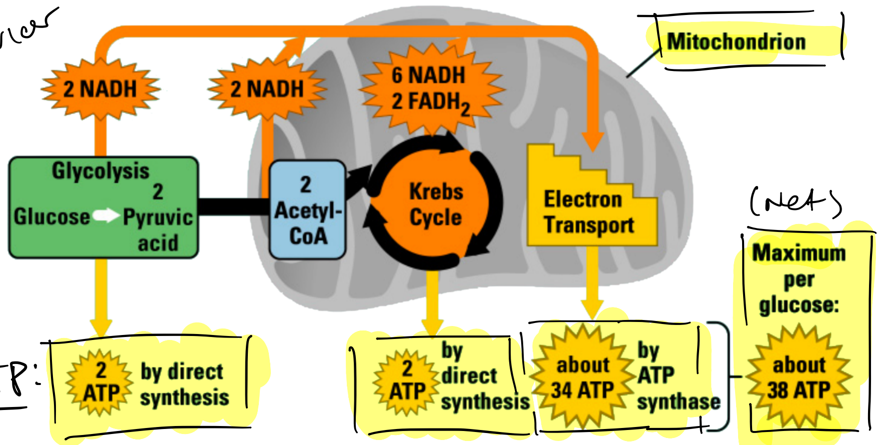
H^+



Summary

cell interior

Net ATP:



know these numbers!

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

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Efficiency

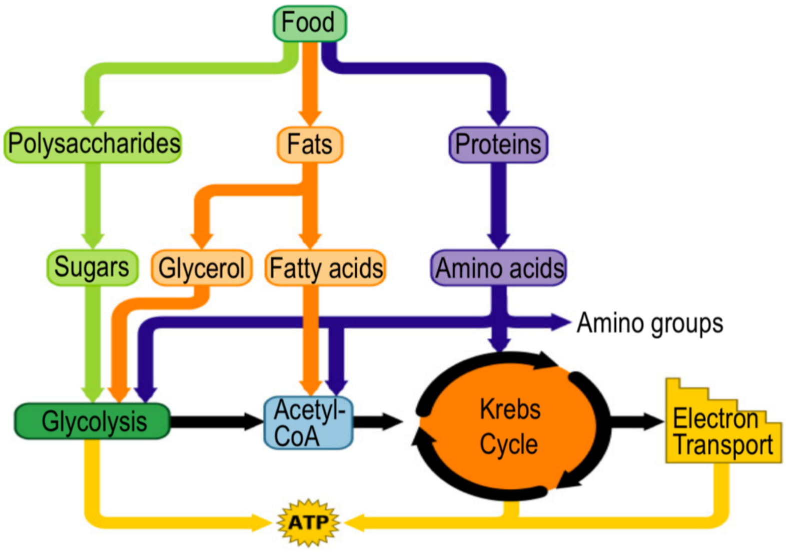
- Free energy available from glucose $\Delta G = -2862\,kJ/mol$
- Cellular respiration: 38 ATP/glucose molecule.
- Free energy available from ATP: $\Delta G = -29\,kJ/mol$

$$\Rightarrow \boxed{\text{Efficiency} = \frac{\text{Output}}{\text{Input}} = \frac{38\,\text{ATP} \times (-29\,kJ/mol)}{-2862\,kJ/mol} \approx 38.5\%}$$

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

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Stage 1 of cellular respiration doesn't require oxygen →

cellular respiration
1. Glycolysis } anaerobic
2. Krebs } aerobic
3. Electron.

⇒ 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 O_2 during electron transport)

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

- lactic acid (human muscles)
- ethanol & CO_2 (yeast)

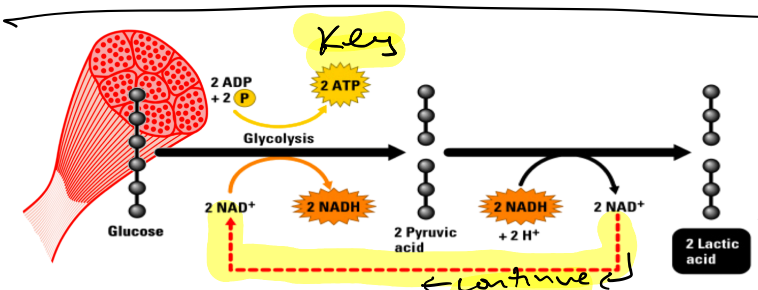
↳ allows glycolysis to continue

→ examples

Fermentation

- Human muscle cells (during intense exercise → not enough O_2)

Fermentation producing lactic acid:
Note: not cause of burning sensation! (Actually tends to counteract)



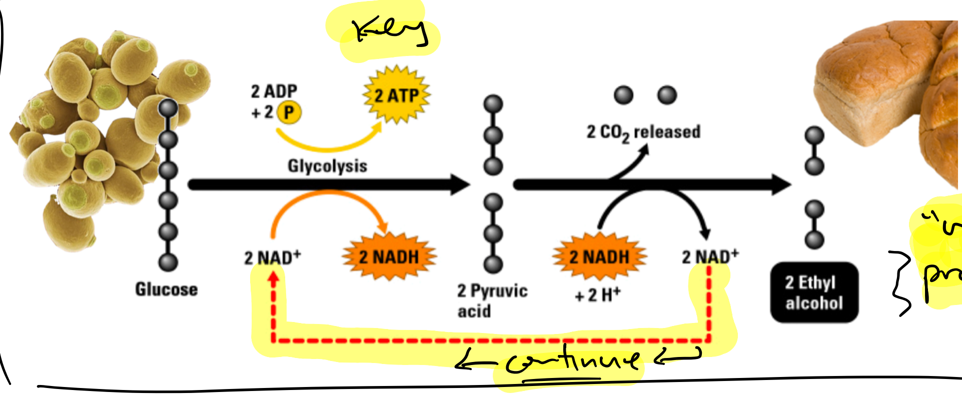
waste product

Figure 42: Human muscle cells. Oxygen is supplied to your muscles via the blood stream for aerobic cellular respiration to take place to make ATP. However, during exercise, the supply of oxygen can be insufficient and ATP must be made anaerobically, leading to lactic acid.

- Micro-organisms/bacteria (eg yeast)

→ can perform both { respiration / fermentation

Fermentation producing ethanol & CO_2



"waste" product } usually desired!

- Industrial fermentation (bulk growth of micro organisms, producing useful by-products)
  - biofuels
  - antibiotics
  - feedstock

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 net)
✓ 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 $\Delta G = -2862$ kJ/mol under standard conditions. In respiration, ATP molecules are synthesised for each glucose molecule, as follows:

$$C_6H_{12}O_6 + 6O_2 + 38\ ADP + 38\ P \rightarrow 6CO_2 + 6H_2O + 38\ ATP$$

Under standard conditions, each ATP can contribute $\Delta G = -29$ 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: B

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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:

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