How Cells Release Chemical Energy – Cellular Respiration
Overview of Cellular Respiration

- Produces ATP molecules
- Requires oxygen
- Releases carbon dioxide
- The reverse of photosynthesis
Why is it called cellular respiration???

- What is respiration?
- What do we breathe in?
- What do we breathe out?

Well, your cells do the same thing!!!

- Cellular respiration is why you breathe!
Oxidation & Reduction happens in Cellular Respiration

- Oxidation = removal of hydrogen atoms
- Reduction = addition of hydrogen atoms

Hydrogens removed from glucose = CO₂

Oxygen accepts hydrogens = water

\[
\text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2 \rightarrow 6\text{CO}_2 + 6\text{H}_2\text{O} + \text{energy}
\]
Phases of complete glucose breakdown aka your ham sandwich!

- Glucose broken down in steps
  - More efficient way to capture energy & make ATP
- Coenzymes (non-protein) enzymes join with hydrogen and e^-
  - \( \text{NAD}^+ \rightarrow \text{NADH} \)
  - \( \text{FAD} \rightarrow \text{FADH}_2 \)
The 4 phases of glucose breakdown:

1. Glycolysis
2. Preparatory reaction
3. Citric acid cycle
4. Electron transport chain

Glycolysis:
- glucose → pyruvate
- 2 ATP

Preparatory reaction:
- NADH and FADH₂
- e⁻

Citric acid cycle:
- 2 ATP

Electron transport chain:
- 34 ATP
Glycolysis: Glucose Breakdown Starts

- Happens in cytoplasm of all prokaryotic and eukaryotic cells
- 1 glucose (6C) broken down into 2 pyruvates (3C)
- Two steps
  1. energy requiring
  2. energy harvesting
• Energy-investment steps
  – 2 ATP transfer phosphates to glucose
  – Activates them for next steps

• Energy-harvesting steps
  – Substrate-level ATP synthesis produces 4 ATP
  • Net gain of 2 ATP
  – 2 NADH made
Products of Glycolysis

- **Net yield of glycolysis:**
  - 2 pyruvate, 2 ATP, and 2 NADH per glucose

- **Pyruvate may:**
  - Enter fermentation pathways in cytoplasm (is reduced)
  - Enter mitochondria and be broken down further in aerobic respiration

![Glycolysis diagram](image)

Glycolysis

<table>
<thead>
<tr>
<th>inputs</th>
<th>outputs</th>
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<tbody>
<tr>
<td>glucose</td>
<td>2 pyruvate</td>
</tr>
<tr>
<td>2 NAD$^+$</td>
<td>2 NADH</td>
</tr>
<tr>
<td>2 ATP</td>
<td>2 ADP</td>
</tr>
<tr>
<td>4 ADP + 4 $P$</td>
<td>4 ATP net</td>
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7.3 Inside the Mitochondria

- Other 3 phases take place inside the mitochondria

1. Glycolysis - cytoplasm
2. Preparatory reaction
3. Citric acid cycle
4. Electron transport chain
2. Preparatory reaction: acetyl-CoA formation

- Occurs in mitochondrial matrix – pyruvate split & oxidized
- Produces acetyl-CoA (2 per glucose molecule)
- $CO_2$ molecule given off (2 per glucose molecule)
- $NAD^+$ → NADH (2 per glucose molecule)
3. Citric Acid Cycle (also called the Krebs Cycle)

- Occurs in mitochondrial matrix
- Acetyl CoA transfer acetyl group to C₄ molecule – produces citric acid (6C)
- Acetyl group oxidized to carbon dioxide – all C gone (glucose completely broken down!)
- NAD⁺ → NADH and FAD → FADH₂
- Substrate-level ATP synthesis produces ATP
- Two cycles for each glucose molecule

Citric acid cycle inputs and outputs:

<table>
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<th>Inputs</th>
<th>Outputs</th>
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<tr>
<td>2 acetyl-CoA</td>
<td>4 CO₂</td>
</tr>
<tr>
<td>6 NAD⁺</td>
<td>6 NADH</td>
</tr>
<tr>
<td>2 FAD</td>
<td>2 FADH₂</td>
</tr>
<tr>
<td>2 ADP + 2 P</td>
<td>2 ATP</td>
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</table>
Each $C_2$ acetyl group combines with a $C_4$ molecule to produce citric acid, a $C_6$ molecule.

The loss of two $CO_2$ results in a new $C_4$ molecule.

ATP is produced by substrate-level ATP synthesis.

The citric acid cycle inputs and outputs are:

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Additional oxidation reactions produce another NADH and an FADH$_2$ and regenerate the original $C_4$ molecule.

Twice over, oxidation reactions produce NADH, and $CO_2$ is released.
Please note that due to differing operating systems, some animations will not appear until the presentation is viewed in Presentation Mode (Slide Show view). You may see blank slides in the “Normal” or “Slide Sorter” views. All animations will appear after viewing in Presentation Mode and playing each animation. Most animations will require the latest version of the Flash Player, which is available at http://get.adobe.com/flashplayer.

During glycolysis, glucose is broken down to pyruvate.
1. Remember that there are 2 pyruvate molecules from glycolysis!!

- **Acetyl-CoA** transfers 2C to 4C molecule, forming citrate (6C)
- **CO₂** released
- **NAD⁺** picks up hydrogen and electrons, forming NADH
  - Ditto! – C’s of pyruvate are now all gone!
- **FAD** picks up hydrogen and electrons, forming FADH₂
  - Substrate-level phosphorylation
  - **ATP**
The Results of the 1st 3 stages!!!

- In acetyl Co-A formation and citric acid cycle:
  - Six CO$_2$, two ATP, eight NADH, and two FADH$_2$ for every two pyruvates

- Adding the yield from glycolysis, the total is
  - Twelve reduced coenzymes and four ATP for each glucose molecule

- Coenzymes deliver electrons and hydrogen to the electron transport chain!!!
Aerobic Respiration’s Big Energy Payoff

4. Electron Transport Chain

Many ATP are formed during the third and final stage of aerobic respiration

- Occurs in cristae of mitochondria
- Electrons are passed from one carrier molecule to another
- NADH & FADH₂ deliver electrons
4. The electron transport chain: path of e\textsuperscript{-} & H\textsuperscript{+}

- Coenzymes NADH and FADH\textsubscript{2} donate electrons and H\textsuperscript{+} to electron transfer chains
- As e\textsuperscript{-} go through transport chain, H\textsuperscript{+} gets shuttled out (via active transport), forming a H\textsuperscript{+} concentration gradient
ATP Formation – let’s follow the $H^+$

$H^+$ concentration is now greater in the outer compartment. $H^+$ follows these gradients through ATP synthases to the interior, forming ATP
Let’s follow the e⁻

Finally, oxygen accepts electrons and combines with H⁺, forming water.
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During glycolysis and the tricarboxylic acid cycle, oxidation of organic molecules results in production of reduced coenzymes such as NADH.
**Summary: The Energy Harvest**

- **Energy yield from glucose metabolism**
  - Maximum of 38 ATP made
  - Some cells make only 36 ATPs or less
  - 36-38 ATP about 40% of available energy in a glucose molecule
  - Rest is lost as heat

<table>
<thead>
<tr>
<th>Phase</th>
<th>NADH</th>
<th>FADH&lt;sub&gt;2&lt;/sub&gt;</th>
<th>ATP Yield</th>
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<tbody>
<tr>
<td>Glycolysis</td>
<td>2</td>
<td>_</td>
<td>2</td>
</tr>
<tr>
<td>Prep reaction</td>
<td>2</td>
<td>_</td>
<td>_</td>
</tr>
<tr>
<td>Citric acid cycle</td>
<td>6</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Electron transport chain</td>
<td>10</td>
<td>2</td>
<td>30</td>
</tr>
<tr>
<td><strong>Total ATP</strong></td>
<td></td>
<td></td>
<td>38</td>
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Summary: Aerobic Respiration

A. First stage: Glucose is converted to 2 pyruvate, 2 NADH and 4 ATP form. An energy investment of 2 ATP began the reactions, so the net yield is 2 ATP.

B. Second stage: 10 more coenzymes accept electrons and hydrogen ions during the second-stage reactions. All six carbons of glucose leave the cell (as 6 CO₂), and 2 ATP form.

C. Coenzymes donate electrons and hydrogen ions to electron transfer chains. Energy lost by the electrons as they flow through the chains is used to move H⁺ across the membranes. The resulting gradient causes H⁺ to flow through ATP synthases, driving ATP synthesis.
What if you’re on a low-carb diet (not so much glucose)???

Alternative metabolic pathways
- Cells use other energy sources

There are C’s in proteins!
There are C’s in lipids!
Anaerobic Energy-Releasing Pathways: Fermentation

- Oxygen is required for the complete breakdown of glucose
- Fermentation pathways break down carbohydrates without using oxygen (anaerobic)
- The final steps in these pathways regenerate NAD\(^+\) but do not produce ATP – only glycolysis for ATP!

Only 2 ATP per glucose molecule!!!
Fermentation in animal cells

- Pyruvate reduced to lactate in muscle cells
- Provides brief burst of energy when no oxygen
- Recovery from oxygen deficit complete when enough oxygen is present to completely break down glucose – why you breathe hard!

Fermentation

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Pyruvate reduced to lactate in muscle cells. Provides brief burst of energy when no oxygen. Recovery from oxygen deficit complete when enough oxygen is present to completely break down glucose – why you breathe hard!
Fermentation

Bacteria & yeast (unicellular fungus) use fermentation to produce:
- lactate or other organic acids
- alcohol (ethanol) and carbon dioxide
- yogurt, wine, beer, leavening of bread, sauerkraut, dry sausages, kimchi, vinegar

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Reflections on Life’s Unity – The Circle of Life!

- Photosynthesizers use energy from the sun to feed themselves and other forms of life
- Aerobic respiration balances photosynthesis