BIO 311C
Spring 2010

Lecture 26 – Friday 2 Apr.

Consider three aspects of respiration:

- Carbon flow

- Oxidations and reductions

- Energy changes

Each of these aspects can be considered for respiration as a whole, and each aspect can also be considered for separate metabolic pathways of respiration.

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Summary of Carbon Flow in Respiration

$$1 \text{ of } C_6 \longrightarrow 6 \text{ of } C_1$$

Recall that: C_6 indicates a chemical compound containing 6 carbon atoms.

C_1 indicates a chemical compound containing 1 carbon atom.

respiration

$$\underbrace{C_6H_{12}O_6}_{C_6 \text{ (a hexose)}} + 6\ O_2 \xrightarrow{\text{respiration}} 6\ \underbrace{CO_2}_{C_1} + 6\ H_2O$$

energy

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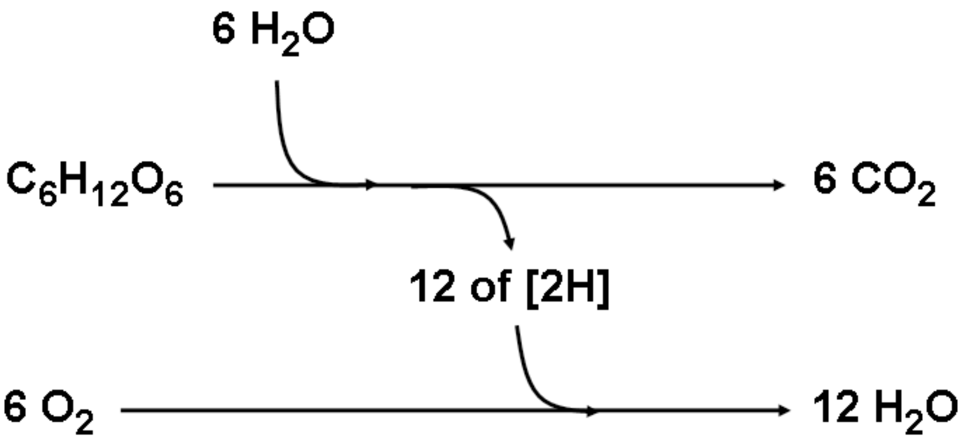
Oxidation and Reduction in Respiration

Energy (ATP) production is not shown in this illustration.



Respiration shown as coupled oxidation and reduction half-reactions.

oxidation

$$C_6H_{12}O_6 + 6\ O_2 \xrightarrow{\textit{respiration}} 6\ CO_2 + 6\ H_2O$$

reduction

Respiration, showing which reactant is oxidized and which reactant is reduced.

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Energy Capture During Respiration

$$C_6H_{12}O_6 + 6\ O_2 \longrightarrow 6\ CO_2 + 6\ H_2O \qquad \Delta G^\circ = -\ 2880\ \text{kJ/mole}$$

$$36\ \{\ ADP + P_i\ \} \qquad 36\ \{\ ATP + H_2O\ \} \qquad \Delta G^\circ = +\ 1080\ \text{kJ/mole}$$

$$\text{Sum:} \qquad \Delta G^\circ = -\ 1800\ \text{kJ/mole}$$

Efficiency of energy conversion: $\dfrac{1080\ \text{kJ/mol}}{2880\ \text{kJ/mol}} \times 100\% \approx 38\%$

Note that 1800 kJ of energy is lost as heat for every mole of glucose that is fully oxidized. Thus, ≈ 62% of the energy released during glucose oxidization is lost. This suggests that respiration is not a very efficient process. However, this heat loss (expressed as a negative ΔG° value) is what drives the process in the forward direction and allows respiration to occur at a rapid rate.

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Metabolic Pathways and Processes that Participate in Respiration

- Glycolysis .... Occurs in the cytoplasmic matrix

- Pyruvate dehydrogenase
- Krebs Cycle
- Mitochondrial electron transport chain
- Oxidative phosphorylation

Occur in mitochondria of eukaryotic cells

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General Description of Glycolysis:

Glycolysis - is a metabolic pathway that:

a. cleaves a C_6 molecule (a hexose - typically glucose) into two, producing two C_3 (pyruvate) molecules;

b. generates two high-energy bonds (by the conversion of 2 (ADP + P_i) to 2 ATP for every C_6 molecule utilized in the pathway;

c. collects two pairs of hydrogen atoms (as 2 NADH) for every C_6 molecule utilized in the pathway.

Thus, glycolysis is a catabolic pathway.

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Glycolysis - showing Initial Reactants and Final Products

$$\text{glucose} + 2(\text{ADP} + \text{P}_i) + 2\,\text{NAD}^+ \xrightleftharpoons{\text{glycolysis}} 2\ \text{pyruvate} + 2(\text{ATP} + \text{H}_2\text{O}) + 2(\text{NADH} + \text{H}^+)$$

ΔG° ≈ - 85 kJ/(mole of glucose)

Thus, glycolysis is a highly exergonic metabolic pathway.

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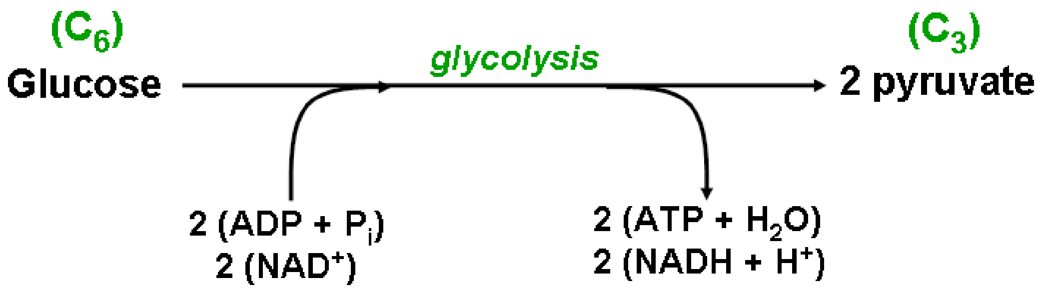
Glycolysis -

Showing glucose breakdown coupled to ATP production and NAD$^+$ reduction:



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carbon flow: $C_6 \longrightarrow 2 \text{ of } C_3$

oxidation and reduction:

oxidation

$$C_6H_{12}O_6 + 2\,NAD^+ \xrightarrow{\textit{respiration}} 2\,Pyr + 2\,(NADH + H^+)$$

reduction

energy capture: $2\,(ADP + P_i) \longrightarrow 2\,(ATP + H_2O)$

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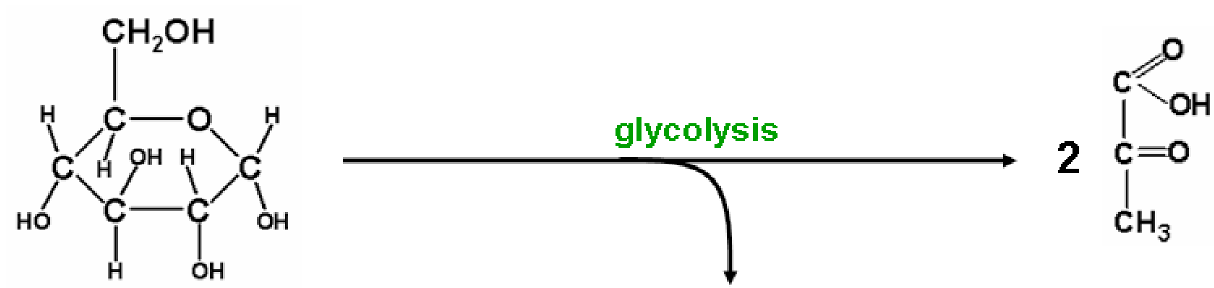
Glycolysis -

showing structural and chemical formulas of the initial reactant glucose and the final product pyruvic acid (pyruvate).



$C_6H_{12}O_6$
D-glucose

2 ATP
2 NADH

$C_3H_4O_3$
pyruvic acid

Note: not all substrates are shown in this representation of glycolysis, although the other substrates (two each of reactants ADP, P_i, NAD^+ and product H^+) are easily deduced from the substrates that are shown.

The ratio of H-atoms to O-atoms in the initial reactant (D-glucose) is 2:1.
The ratio of H-atoms to O-atoms in the final product (pyruvic acid) is 4:3 (less than 2:1).

The chemical formulas demonstrate that 4 hydrogen atoms are lost from each glucose molecule oxidized to pyruvic acid in glycolysis.

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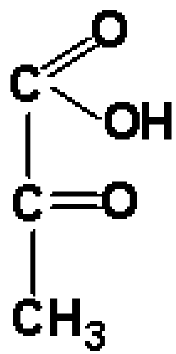
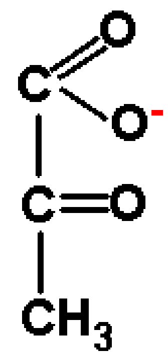
Pyruvic acid vs Pyruvate

The names pyruvic acid and pyruvate are often used interchangeably in describing the final product of glycolysis. Some textbooks use one term while other textbooks use the other term. Yet, they describe different molecular species.



pyruvic acid



pyruvate

The carboxylic acid functional group is not charged.

The carboxylic acid functional group is charged.

Names of protonated carboxylic acids generally end in "-ic acid".

Names of un-protonated carboxylic acids generally end in "ate".

Consider that glycolysis takes place in the cytoplasmic matrix of cells. Then is the final product of glycolysis best described as "pyruvic acid" or is it best described as “pyruvate”?

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Glycolysis can be divided into 2 phases, an "investment" phase and a "pay-off" phase, each of which involves 5 enzyme-catalyzed metabolic reactions.

Phase 1:

glucose $\xrightarrow{\text{investment phase of glycolysis}}$ 2 of C_3-P

2 ATP → 2 ADP

Phase 2:

2 of C_3-P $\xrightarrow{\text{pay-off phase of glycolysis}}$ 2 of oxidized C_3 molecules (pyruvate)

4 ADP + 2 Pi
2 NAD^+

→

4 ATP
2 ($NADH + H^+$)

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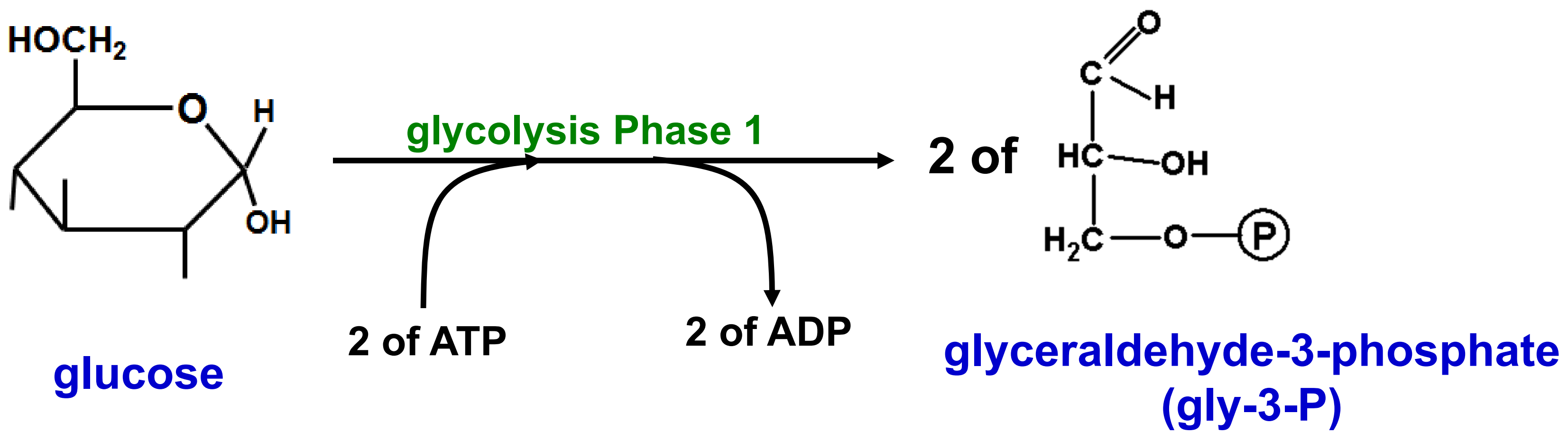
Phase 1 of Glycolysis:



Phase 1 of glycolysis does not oxidize substrate nor collect energy as high energy phosphate bonds. In fact, it uses up 2 high-energy phosphate bonds per glucose.

Note: No P_i is produced during Phase 1 of glycolysis because the phosphate released during ATP hydrolysis is attached to substrate, producing gly-3-P.

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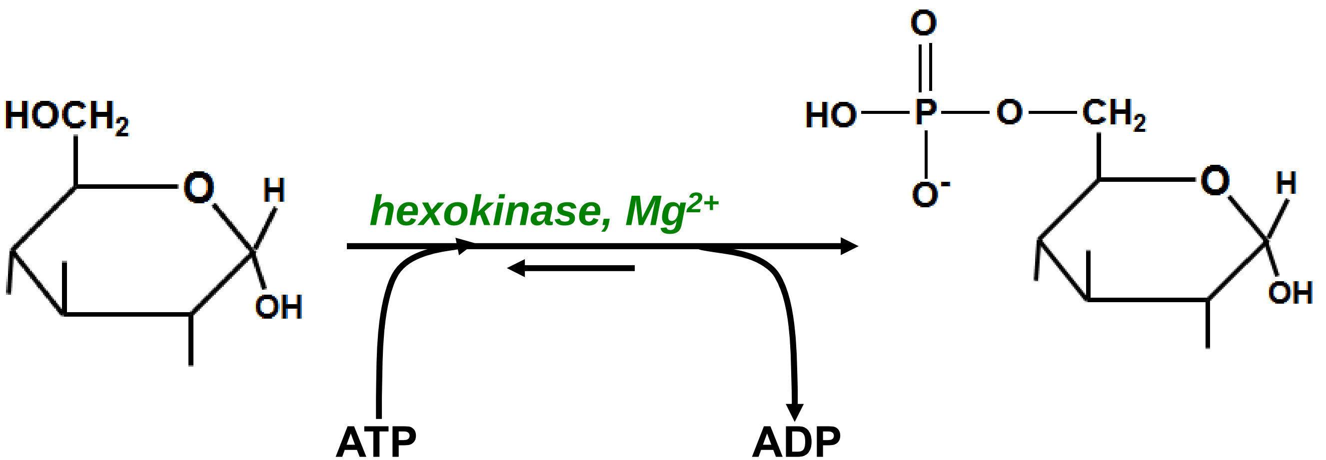
The first reaction of Phase 1 of glycolysis is phosphorylation of glucose, which activates the glucose in preparation for subsequent reactions.



$\Delta G° = - 16$ kJ/mol

All subsequent reactions in glycolysis involve phosphorylated substrate. Only in the last reaction is the substrate de-phosphorylated to give a non-phosphorylated final product.

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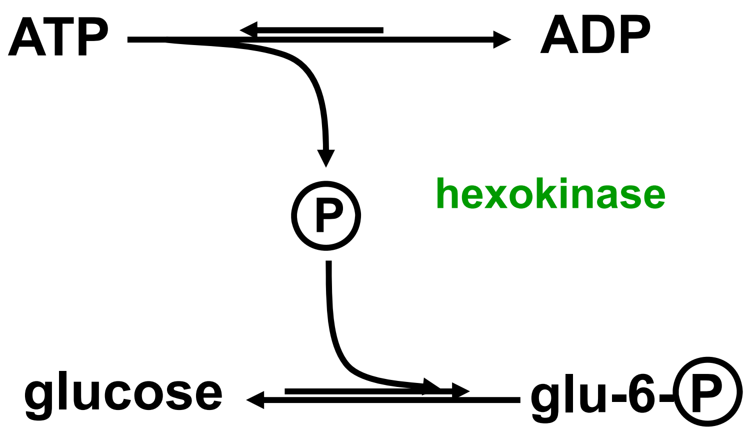
The hexokinase-catalyzed reaction couples an exergonic half-reaction with an endergonic half-reaction in order to drive the endergonic process in the forward direction.

[See Lecture 23, slide 5]



$\Delta G°$ = - 30 kJ/mol

$\Delta G°$ = + 14 kJ/mol

Complete reaction

$$\text{ATP + glucose} \underset{}{\overset{\text{hexokinase}}{\rightleftharpoons}} \text{ADP + glu-6-P}$$

$\Delta G°$ = - 16 kJ/mol

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Glycolysis, Shown as Two Coupled Phases

$$\text{Glucose} \xrightarrow{\text{Phase 1: investment phase}} \text{2 of } C_3\text{- P} \xrightarrow{\text{Phase 2: pay-off phase}} \text{2 of (ox. } C_3)$$

2 ATP → 2 ADP

4 ADP + 2 Pi
2 NAD^+
→
4 ATP
2 (NADH + H^+)

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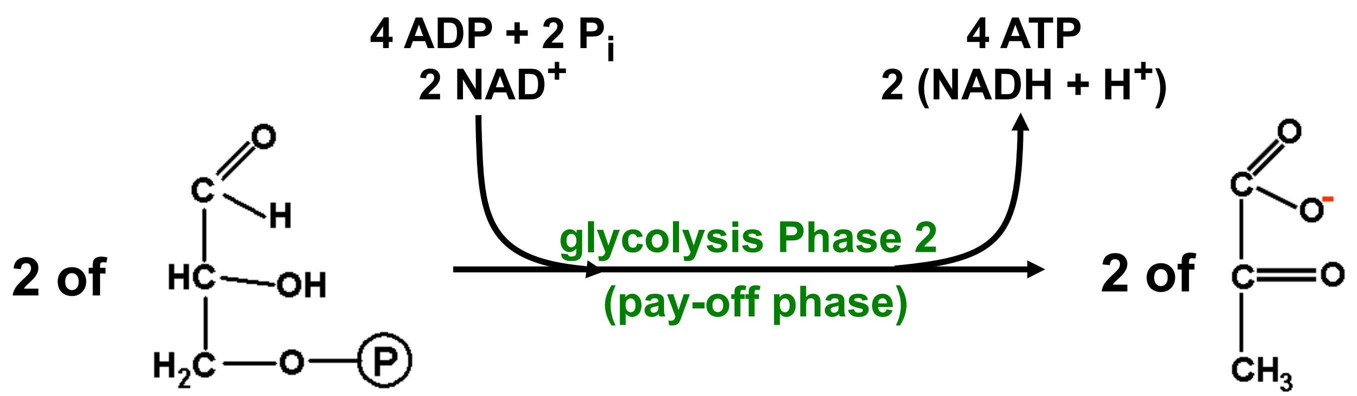
Phase 2 of Glycolysis:



glyceraldehyde-3-phosphate (gly-3-P)
(More reduced substrate)

pyruvate (pyr)
(More oxidized substrate)

Two molecules of substrate are considered instead of one, since two gly-3-P are produced for every glucose molecule that enters glycolysis.

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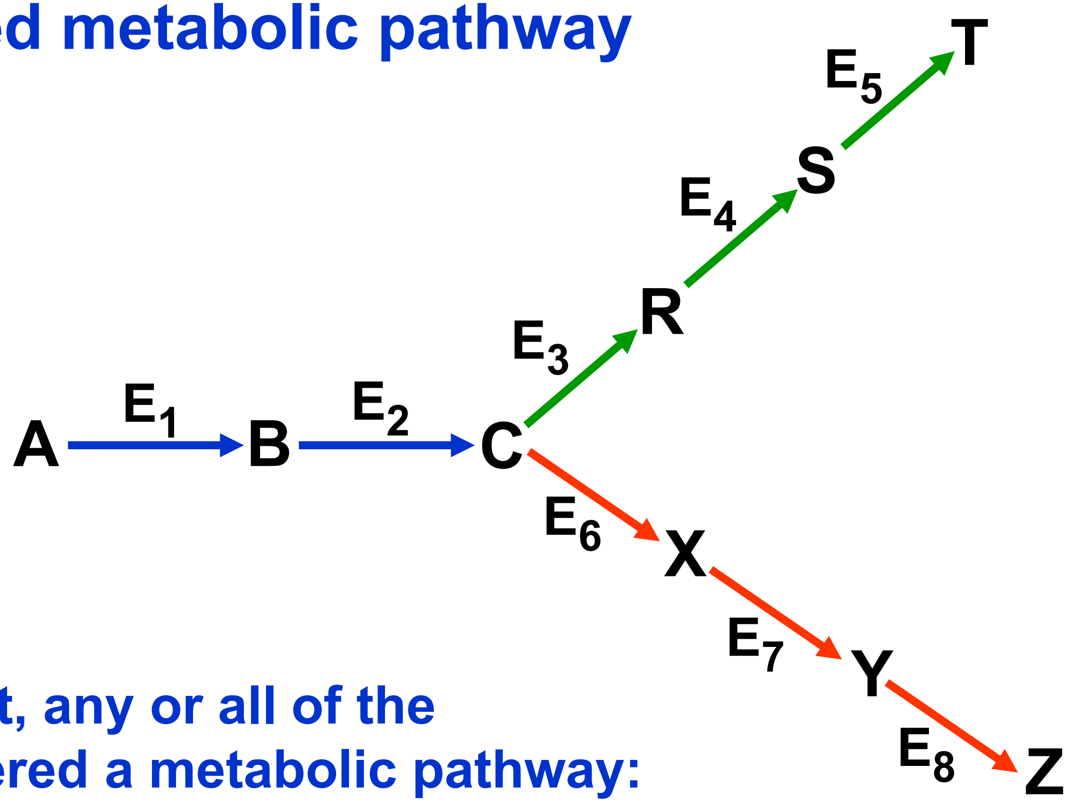
Example of a branched metabolic pathway



Depending on the context, any or all of the following may be considered a metabolic pathway:

A $\longrightarrow$ C

A $\longrightarrow$ T

A $\longrightarrow$ Z

C $\longrightarrow$ T

C $\longrightarrow$ Z

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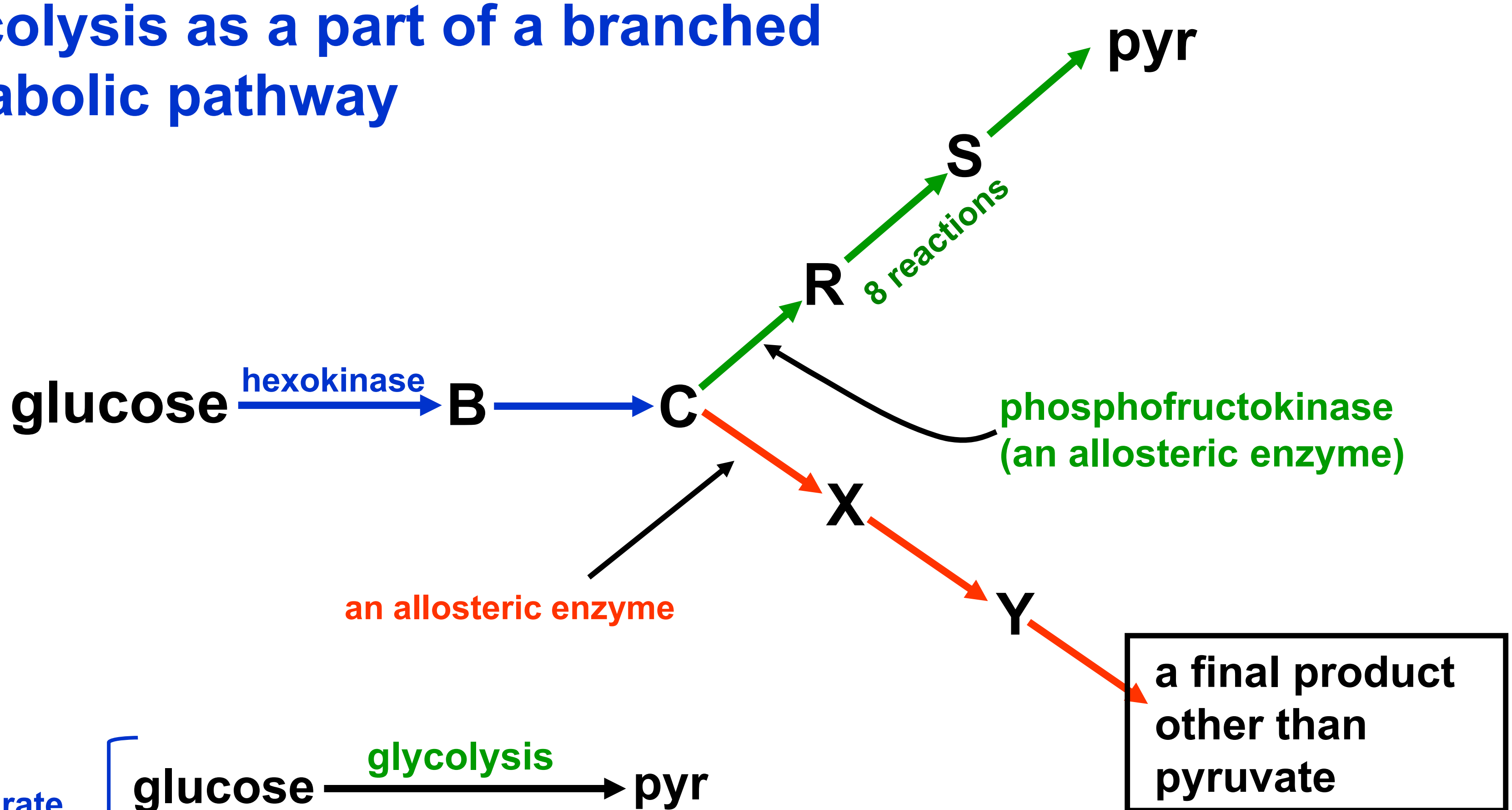
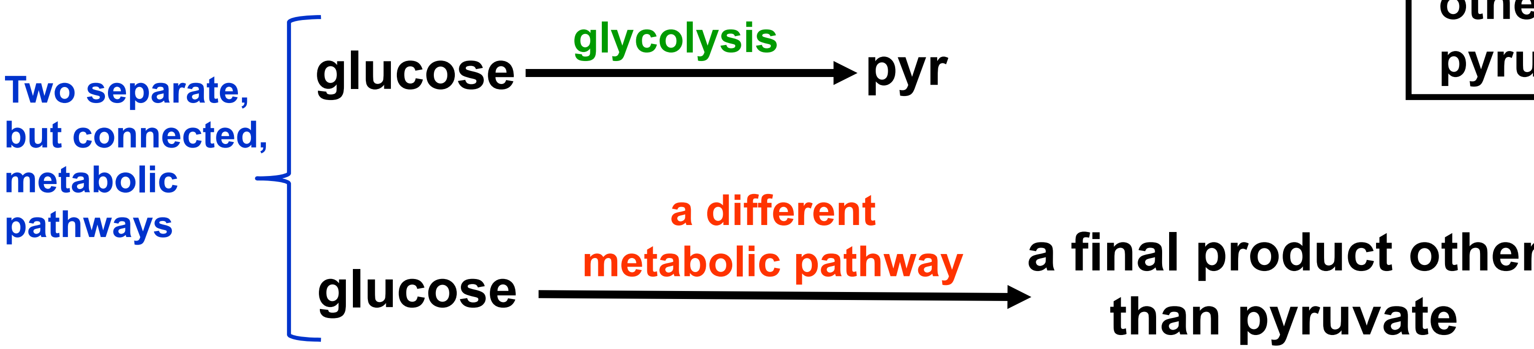
Glycolysis as a part of a branched metabolic pathway





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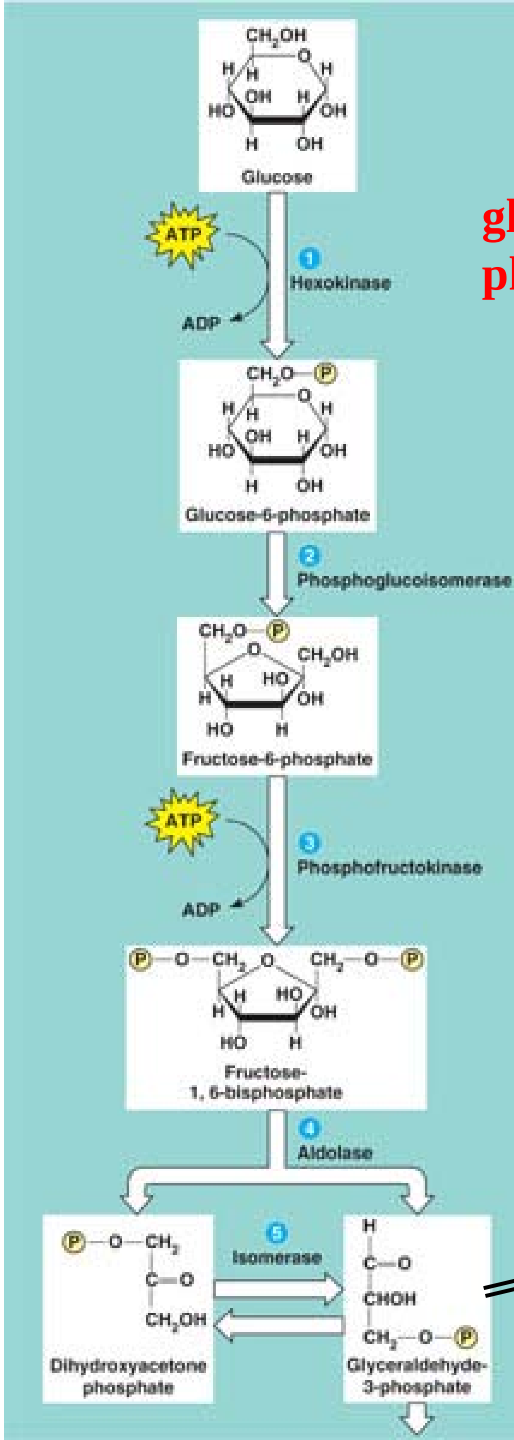
See textbook Fig. 9.21 (p. 181)



glycolysis
phase 1

Regulation of glycolysis at the enzyme phosphofructokinase

See textbook Fig. 9.21 (p. 181)

to phase 2
of glycolysis

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