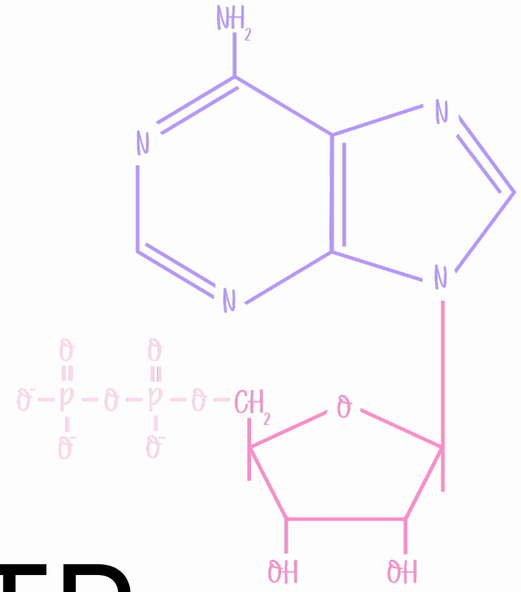
AL-FARABI KAZAKH NATIONAL UNIVERSITY
FACULTY OF BIOLOGY AND BIOTECHNOLOGY
DEPARTMENT OF BIOTECHNOLOGY



Lecture 2

Bioenergetics: The role of ATP

PhD, Acting Associate Professor, Doktyrbay Gulina

Lecture Plan

CONTENTS

1. Introductionto Bioenergetics
2. Exergonicand Endergonic Reactions
3. ATP: Structure and Properties
4. ATP Hydrolysis and the ATP–ADP Cycle
5. ATP and Cellular Work
6. Biological Oxidation
7. Electron Carriers: NAD^+/NADH and FAD/$FADH_2$
8. Respiratory Chain
9. Proton Gradient and Chemiosmosis
10. Oxidative Phosphorylation
11. ATP and Cellular Energy Balance

Learning objectives

By theend of this lecture, students should beable to:

1. Define bioenergetics and explain its importance incellmetabolism.
2. Describe the major forms of energy relevant to biological systems.
3. Explain how cells couple energy-releasing and energy-requiring reactions.
4. Describe the structure and function of ATP.
5. Explain ATP hydrolysis and ATP regeneration.
6. Describe the role of ATP in chemical, transport and mechanical work.
7. Explain the difference between substrate-level phosphorylation and oxidative phosphorylation.
8. Describe, at an overview level, how biological oxidation can lead to ATP production.
9. Explain the basic relationship between the respiratory chain, proton gradient, chemiosmosis and ATP synthesis.

What is bioenergetics?

Bioenergeticsis thestudy of energy transformationsin living systems.
Inbiology, bioenergetics helpsus understandhowcells:

- obtain energy from nutrients or other energy sources;
- convert this energy into usable forms;
- transfer energy between molecules;
- use energy to perform cellular work.

In cellular metabolism, the main focus is:

Energy from nutrients → ATP → cellular work

Major areas of bioenergetics?

Energy storage	**how energy is temporarily stored in chemical or electrochemical form**
Energy production	**how cells obtain usable energy**
Energy utilization	**how cells use energy for biological work**
Energy transfer	**how energy is transferred between molecules**

WHY DO CELLS NEED ENERGY?

Move

Muscle contraction

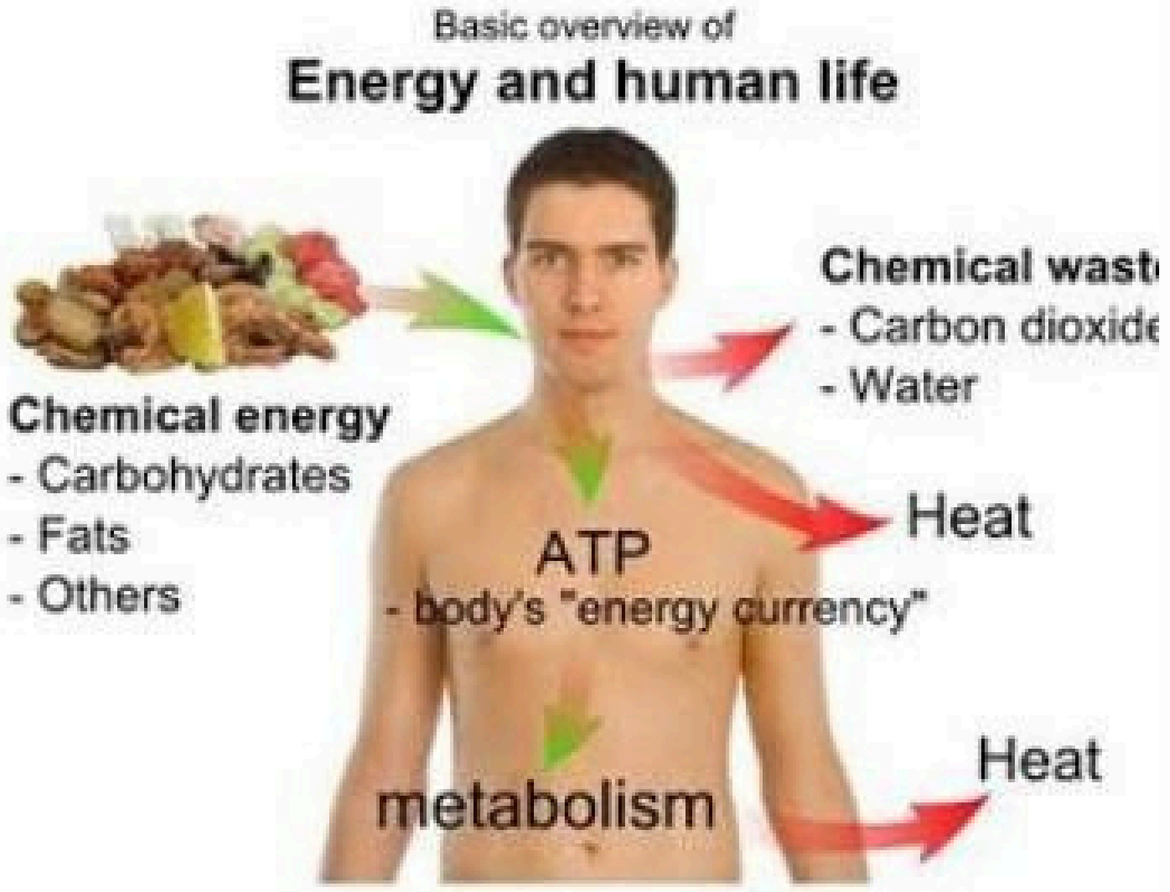
Reproduction

Transport molecules

Remove wastes

Chemical reactions

Energy = the ability to do work



Cells require energy to maintain life.

Energy is required for:

Mechanical work

muscle contraction, movement of molecular motors, cilia and flagella

Active transport

maintaining ion gradients, membrane transport

Biosynthesis

proteins, DNA/RNA, lipids, carbohydrates

Cellular maintenance

maintaining membrane potential, intracellular organization, signal

Free energy and biological reactions

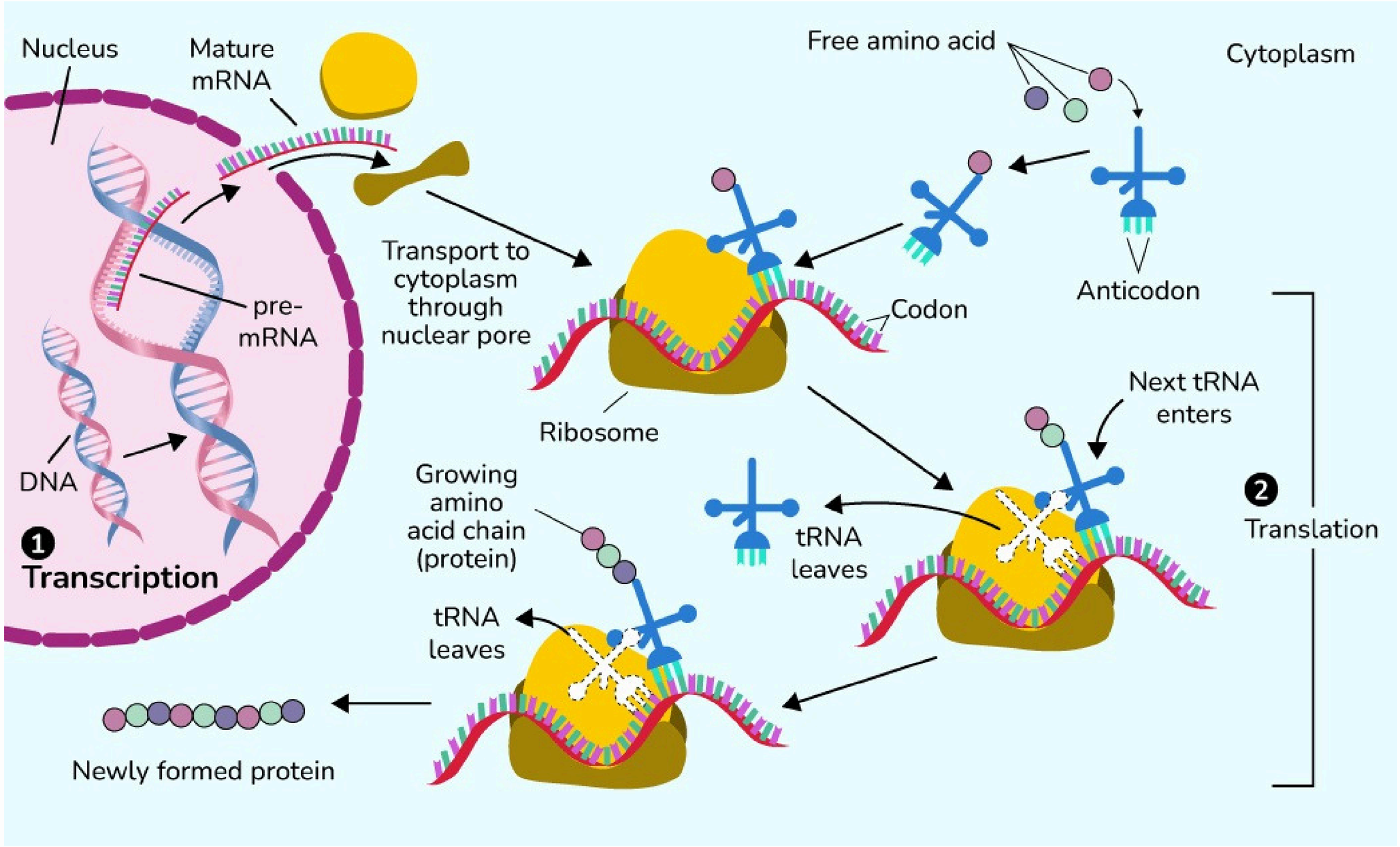
Cells constantly perform chemical reactions that either release or require energy. Gibbs free energy (G) represents the amount of energy available to drive a process under specific conditions.

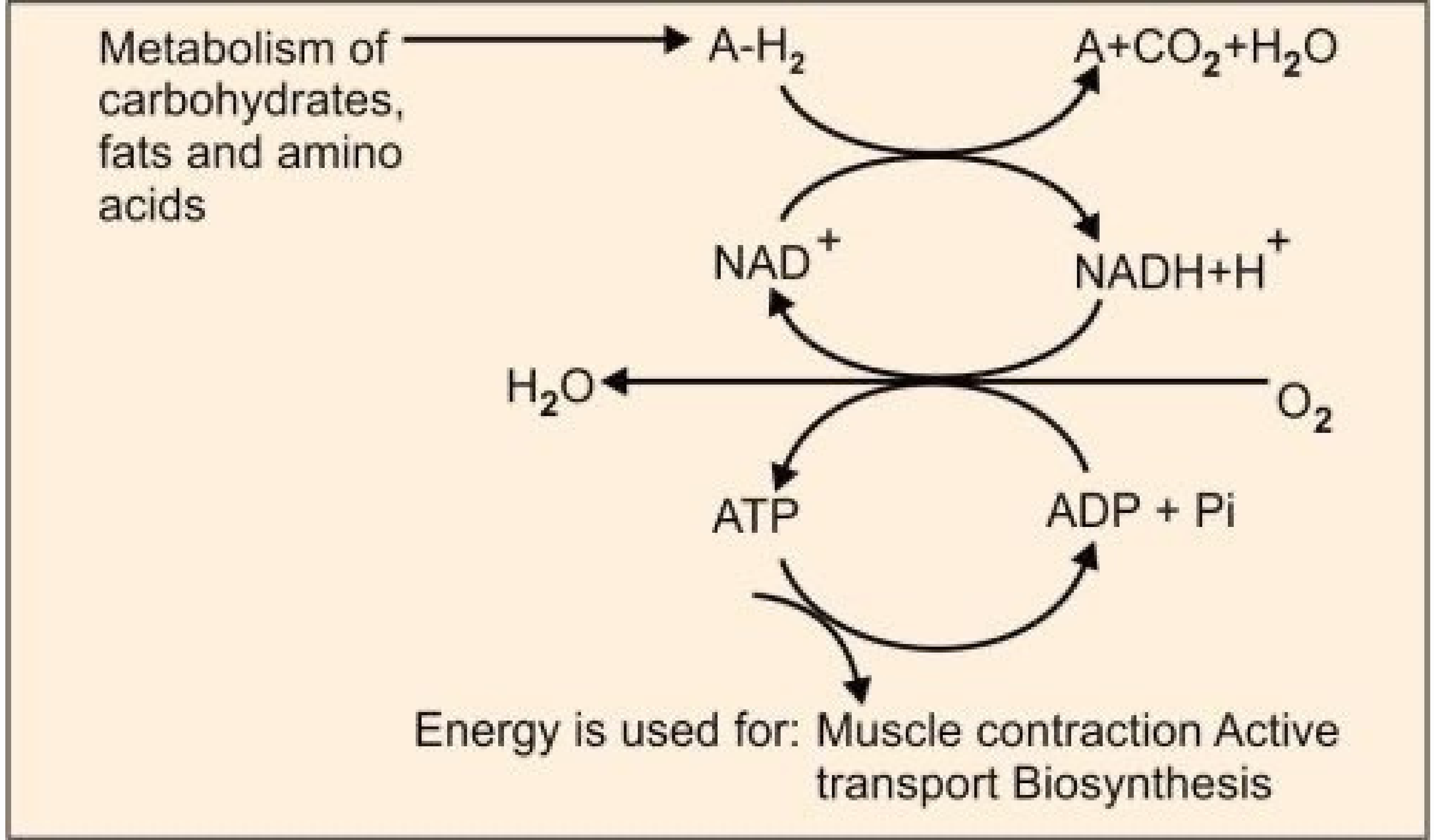
The change in free energy (ΔG) helps determine whether a reaction can proceed spontaneously.

$\Delta G < O$ - the reaction releases free energy and is exergonic. Many catabolic reactions, including the oxidation of nutrients, are exergonic.

$\Delta G > 0$ – the reaction requires an input of free energy and is endergonic. Examples include protein synthesis, DNA synthesis, and active transport.

Protein synthesis

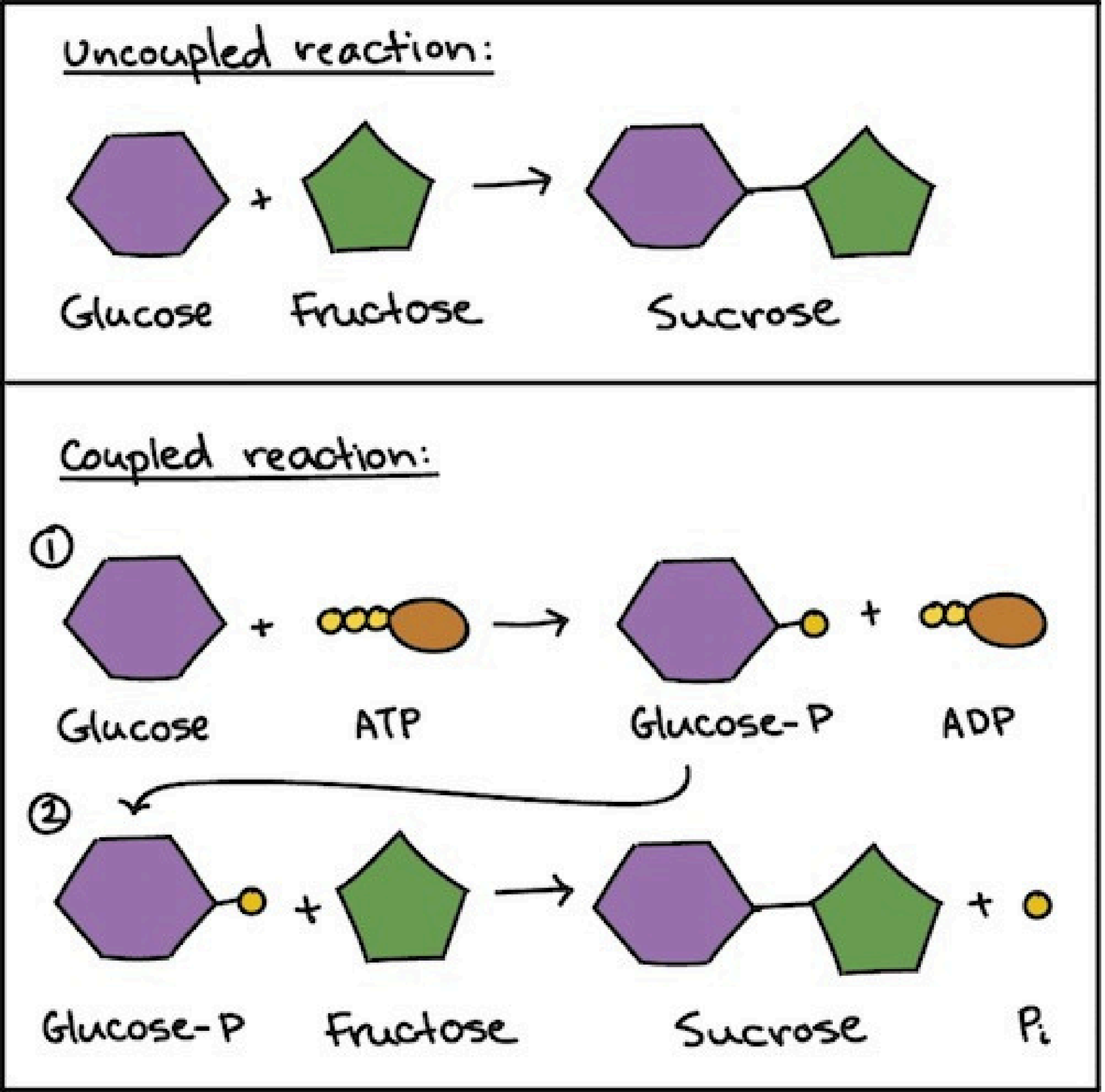



Metabolism of carbohydrates, fats and amino acids
A-H2
A+CO2+H2O
NAD+
NADH+H+
H2O
O2
ATP
ADP + Pi
Energy is used for: Muscle contraction Active transport Biosynthesis

A living cell cannot use the energy released by one reaction simply because another reaction requires energy. The two processes must be connected through a mechanism that allows the released free energy to be transferred and used. This connection between an energy-releasing reaction and an energy-requiring reaction is called **energy coupling**.

For example, the breakdown and oxidation of nutrients such as glucose release free energy. At the same time, the synthesis of proteins, nucleic acids, lipids, and other cellular components requires an input of free energy. The cell couples these processes through energy-transfer molecules, primarily ATP.

Energy released during metabolism is used to convert ADP and inorganic phosphate (Pi) into ATP. ATP can subsequently undergo hydrolysis, releasing free energy that can be coupled to energy-requiring cellular reactions.



Energy-releasing metabolism → ATP formation →
ATP hydrolysis →
cellular work

Therefore, ATP acts as a molecular link between energy production and energy utilization in the cell.

ATP – Adenosine Triphosphate

Adenosine triphosphate (ATP) is the major immediate energy-transfer molecule in living cells. It provides a common mechanism for transferring free energy from metabolic reactions to cellular processes that require energy.

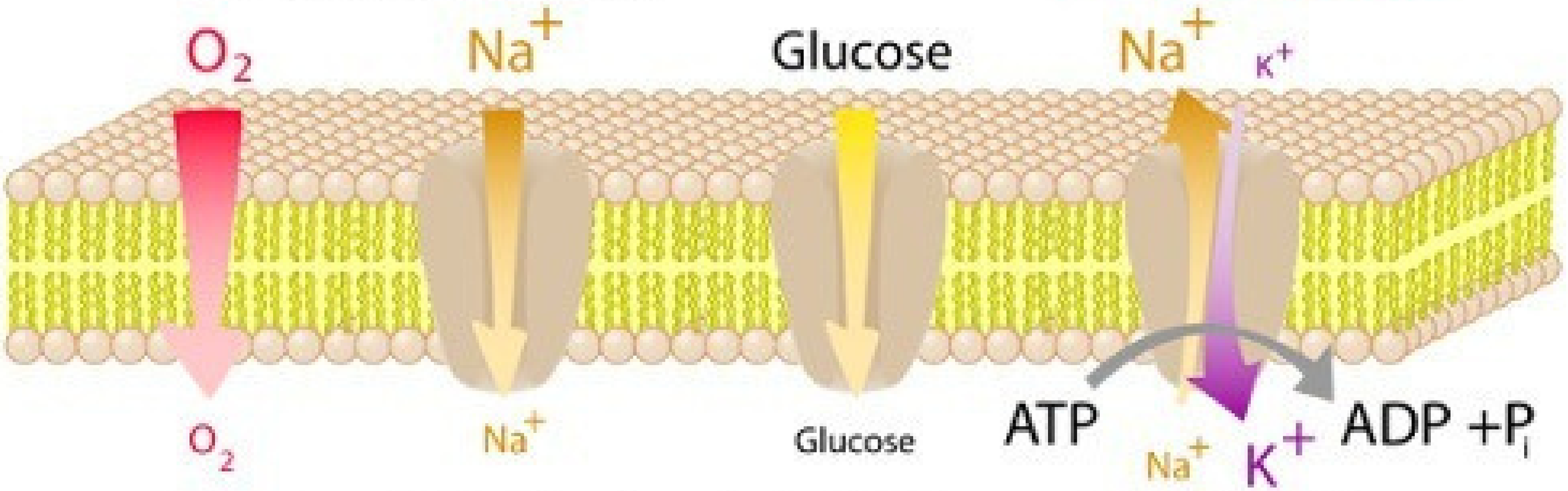
ATP connects energy-releasing metabolic pathways with energy-consuming cellular processes. Energy obtained from nutrients can be used to synthesize ATP, while ATP hydrolysis can then provide energy for cellular work.

ATP is often called the **“energy currency of the cell”** because many different cellular processes use ATP as a common energy-transfer intermediate. Rather than storing energy for long periods, ATP allows energy to be rapidly transferred, used, and regenerated.

ATP does not create energy and is not the main long-term energy store of the cell. It transfers usable free energy between metabolic pathways and cellular work.

Active transport

Passive transport systems involve motion from high concentration toward lower concentrations of the object being transported, and the energy that drives them is just random thermal energy.

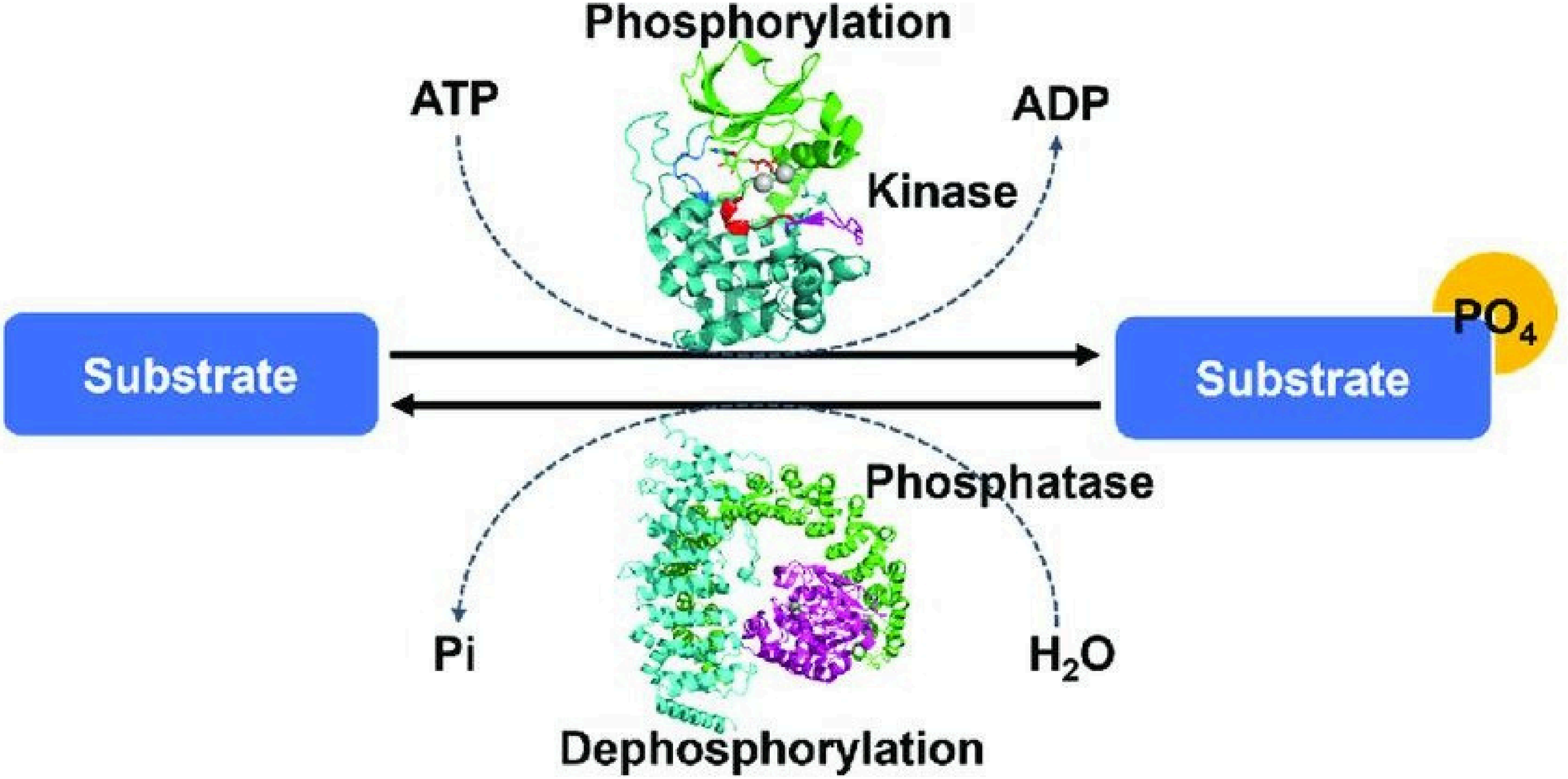


Passive diffusion

Diffusion through aqueous channel

Facilitated diffusion with a carrier protein

Active transport against concentration gradient with input of energy


Phosphorylation
ATP
ADP
Kinase
Substrate
Substrate
PO_4
Phosphatase
Pi
H_2O
Dephosphorylation

ATP is a nucleotide composed of three major structural components: the nitrogenous base adenine, the five-carbon sugar ribose, and three phosphate groups.

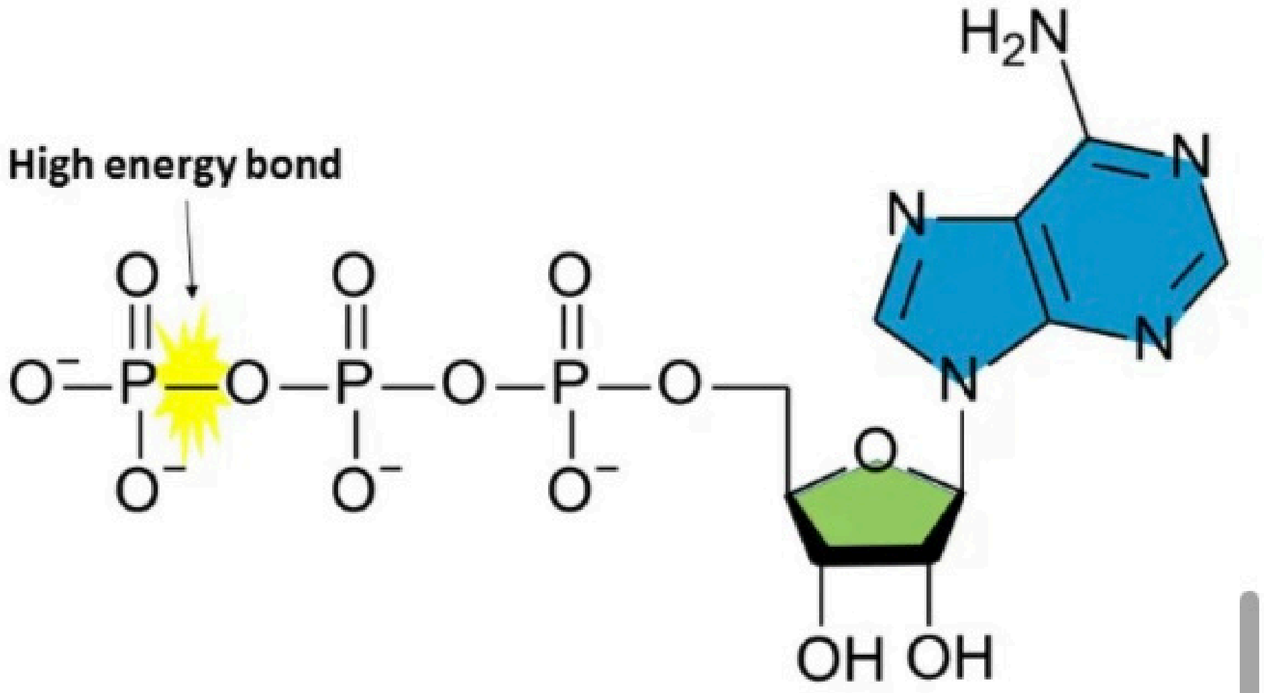
Adenine is attached to ribose through a glycosidic bond, forming the molecule adenosine. The ribose is then linked to three phosphate groups, designated α (alpha), β (beta), and γ (gamma) according to their position relative to the ribose.

Adenine + Ribose = Adenosine

Adenosine + 3 phosphate groups = ATP

The phosphate groups are connected by phosphoanhydride bonds. These bonds are involved in ATP-dependent energy-transfer reactions.

The terminal γ-phosphate is particularly important because it can be transferred to other molecules during phosphorylation reactions or removed during ATP hydrolysis.

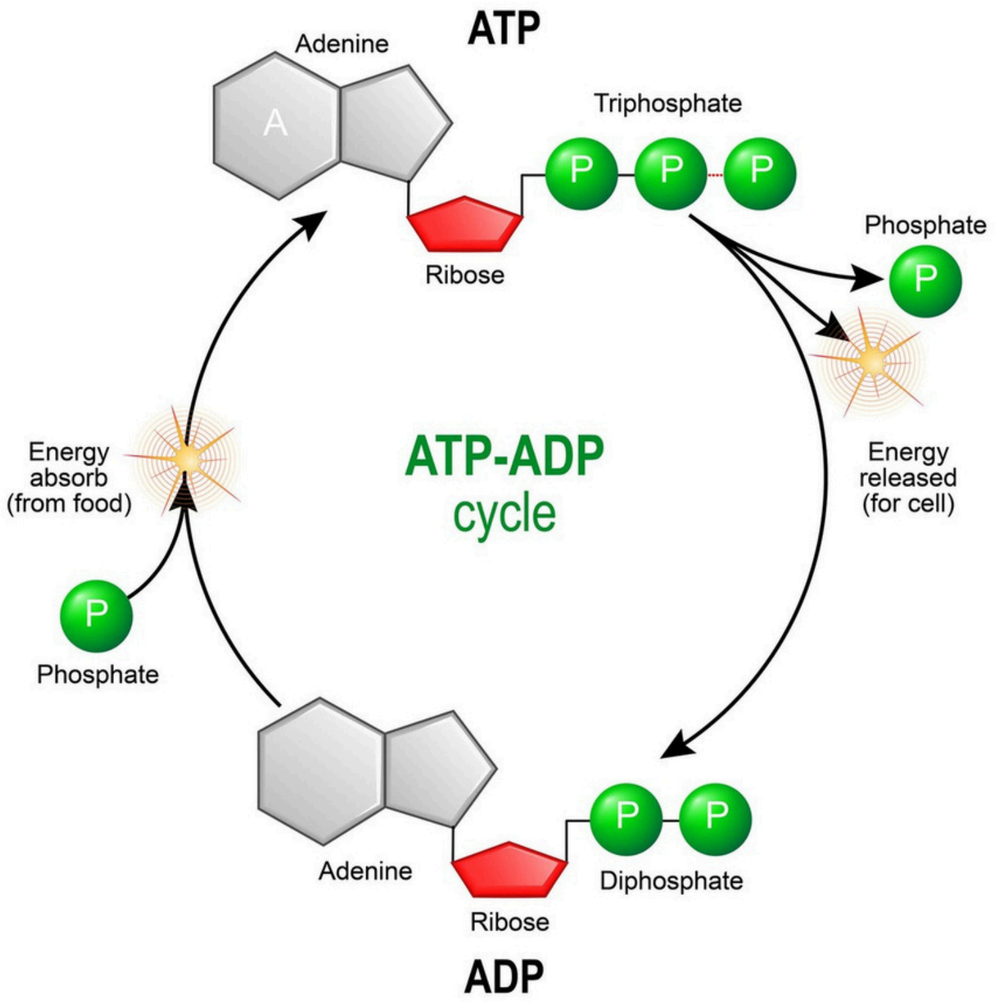


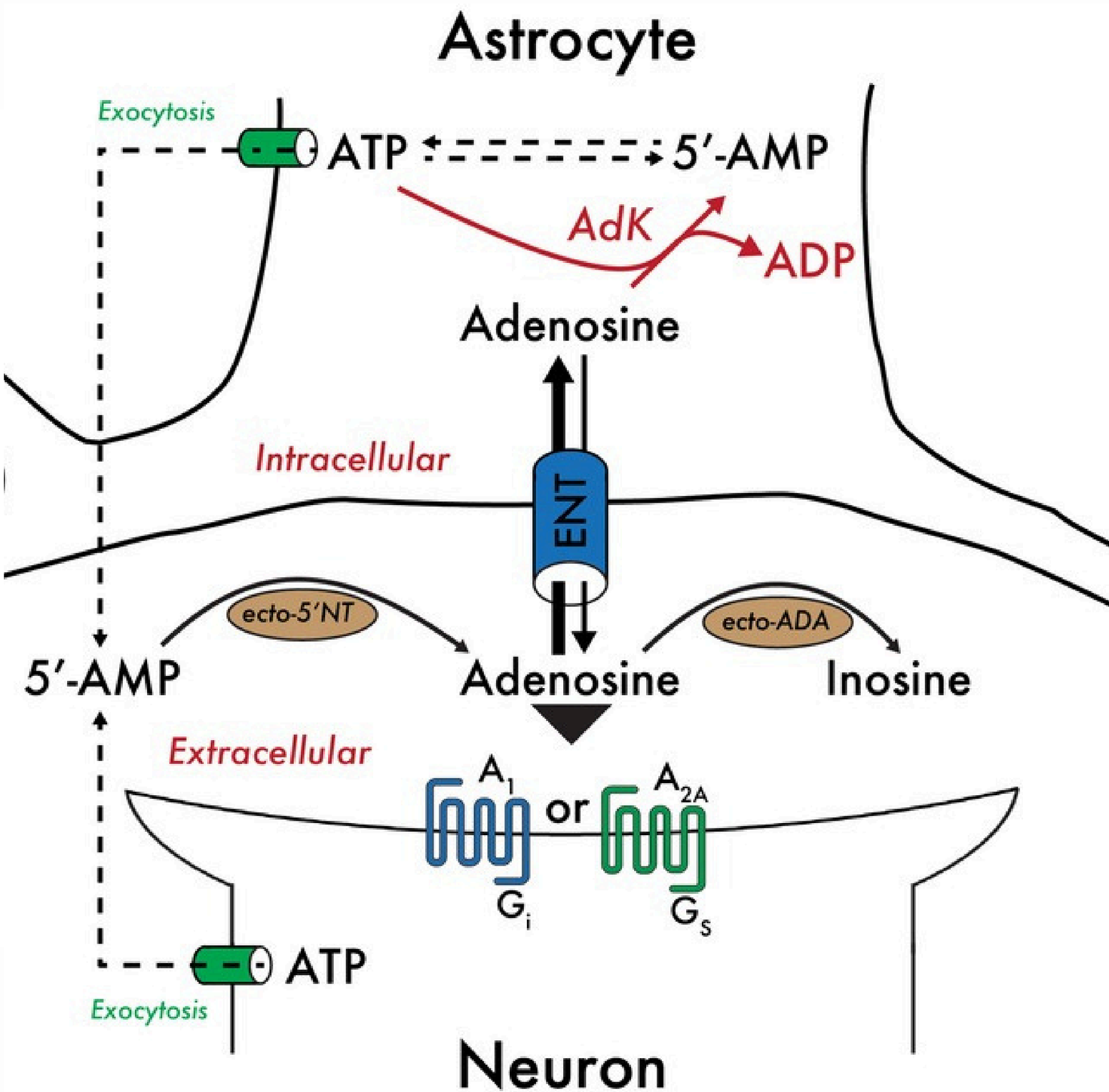
ATP, ADP, and AMP differ in the number of phosphate groups attached to adenosine.
ATP contains three phosphate groups, ADP contains two, and AMP contains one.

ATP can be converted into ADP when the terminal phosphate group is removed or transferred:
$ATP + H_2O \rightarrow ADP + Pi$
In this reaction, Pi represents inorganic phosphate.

ATP can also be converted directly into AMP when two phosphate groups are transferred together as pyrophosphate (PPi):
$ATP + H_2O \rightarrow AMP + PPi$

Pyrophosphate can subsequently be hydrolyzed:
$PPi + H_2O \rightarrow 2\ Pi$
ATP → ADP conversion is particularly common in cellular energy transfer, whereas ATP → AMP occurs in several biosynthetic reactions, including fatty-acid activation and aminoacyl-tRNA formation.
The conversion between ATP, ADP, and AMP therefore reflects different forms of phosphate-group transfer and energy utilization within the cell.


ATP
Adenine
A
Triphosphate
P
P
P
Ribose
Phosphate
P
Energy
released
(for cell)
Energy
absorb
(from food)
ATP-ADP
cycle
P
Phosphate
Adenine
P
P
Diphosphate
Ribose
ADP


Astrocyte
Exocytosis
ATP
5′-AMP
AdK
ADP
Adenosine
Intracellular
ENT
ecto-5′NT
ecto-ADA
5′-AMP
Adenosine
Inosine
Extracellular
A1
or
A2A
Gi
Gs
ATP
Exocytosis
Neuron

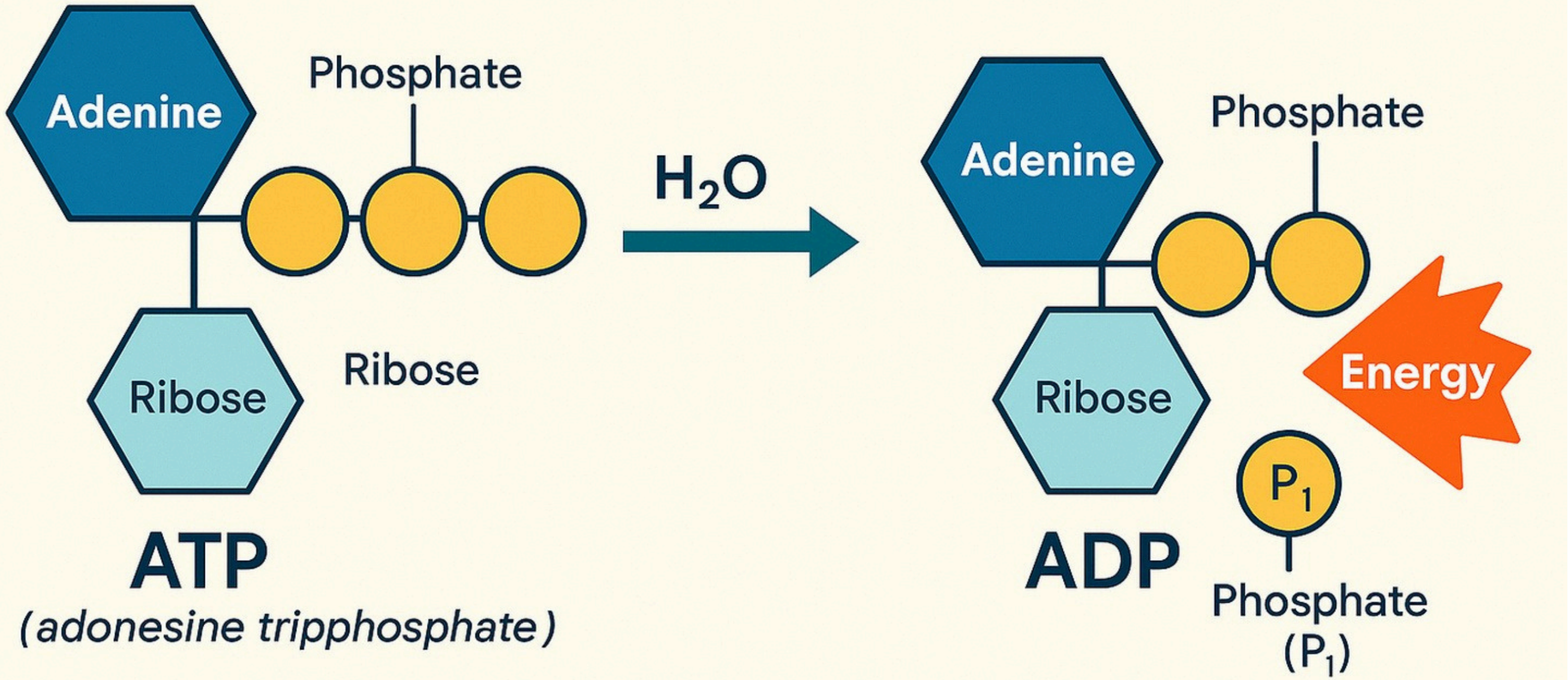
WHY IS ATP SUITABLE FOR ENERGY TRANSFER?

1. **ATP hydrolysis is thermodynamically favorable**
ATP hydrolysis is thermodynamically favorable under physiological conditions. The products of hydrolysis, ADP and inorganic phosphate, have lower free energy than ATP under cellular conditions. Therefore, ATP hydrolysis provide free energy for processes that require energy.

2. ATP can participate in **phosphoryl-group transfer**. The terminal phosphate group can be transferred to proteins, sugars, and other molecules. Phosphorylation can alter the chemical properties, structure, activity, or reactivity of the target molecule and thereby connect ATP hydrolysis with cellular work

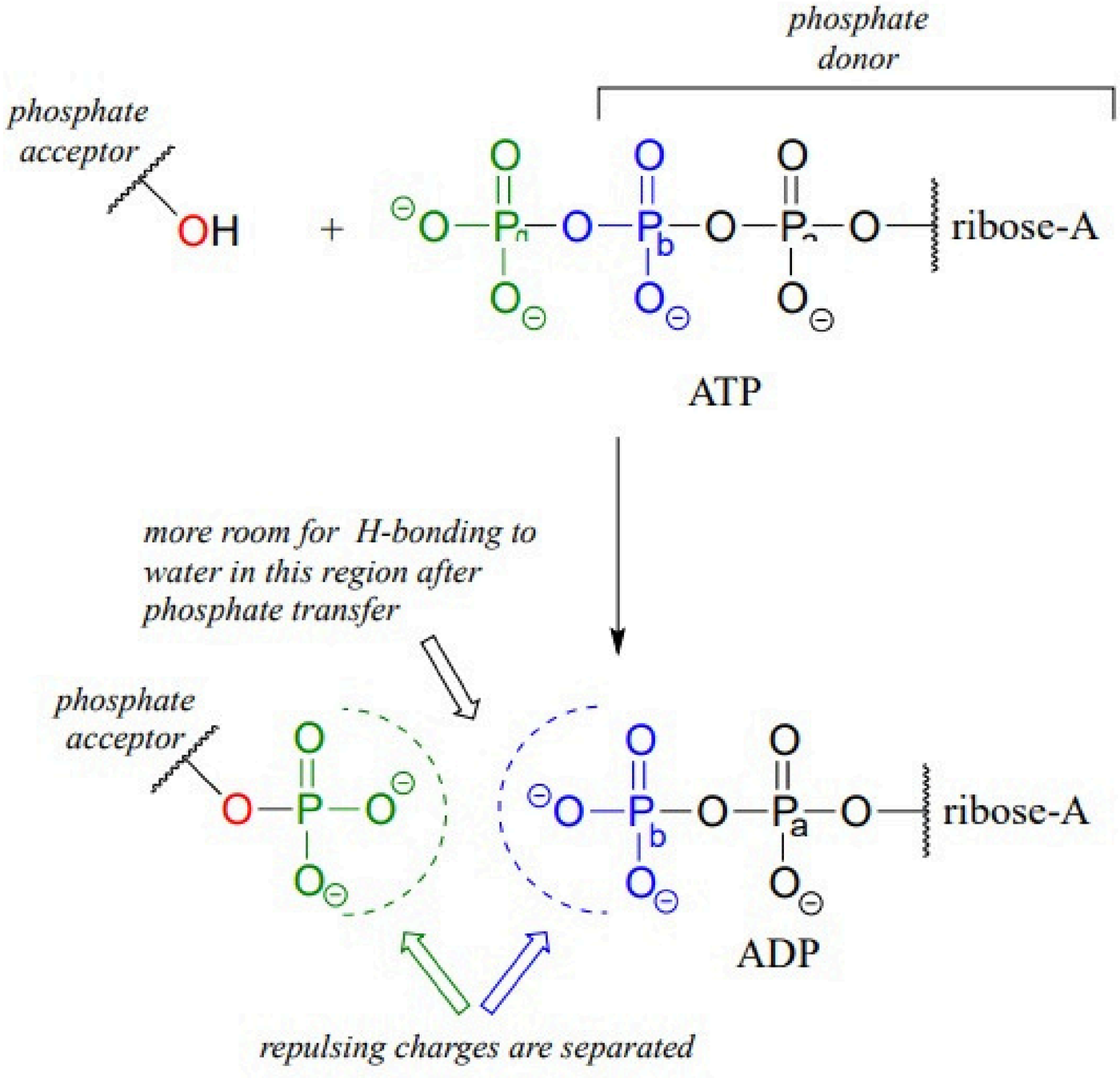
3. **ATP can be rapidly regenerated**. Energy obtained from metabolic pathways can be used to convert ADP and Pi back into ATP. This allows ATP to function as a continuously recycled energy carrier rather than a molecule that is permanently consumed

4. **ATP is kinetically stable in the absence of enzymes**
despite the fact that its hydrolysis is thermodynamically favorable. This is important because it prevents uncontrolled ATP breakdown and allows cells to regulate ATP utilization through specific enzymes.



$ATP + H_2O \rightarrow ADP + Pi + \text{free energy}$

The term hydrolysis refers to a chemical reaction in which a molecule is cleaved through the addition of water.


phosphate donor
phosphate acceptor
OH
+
ribose-A
ATP
more room for H-bonding to water in this region after phosphate transfer
phosphate acceptor
ribose-A
ADP
repulsing charges are separated

From Nutrients to ATP

During biological oxidation, nutrients are gradually oxidized and their electrons are transferred to electron carriers such as NAD^+ and FAD.

NAD^+ → NADH

FAD → $FADH_2$

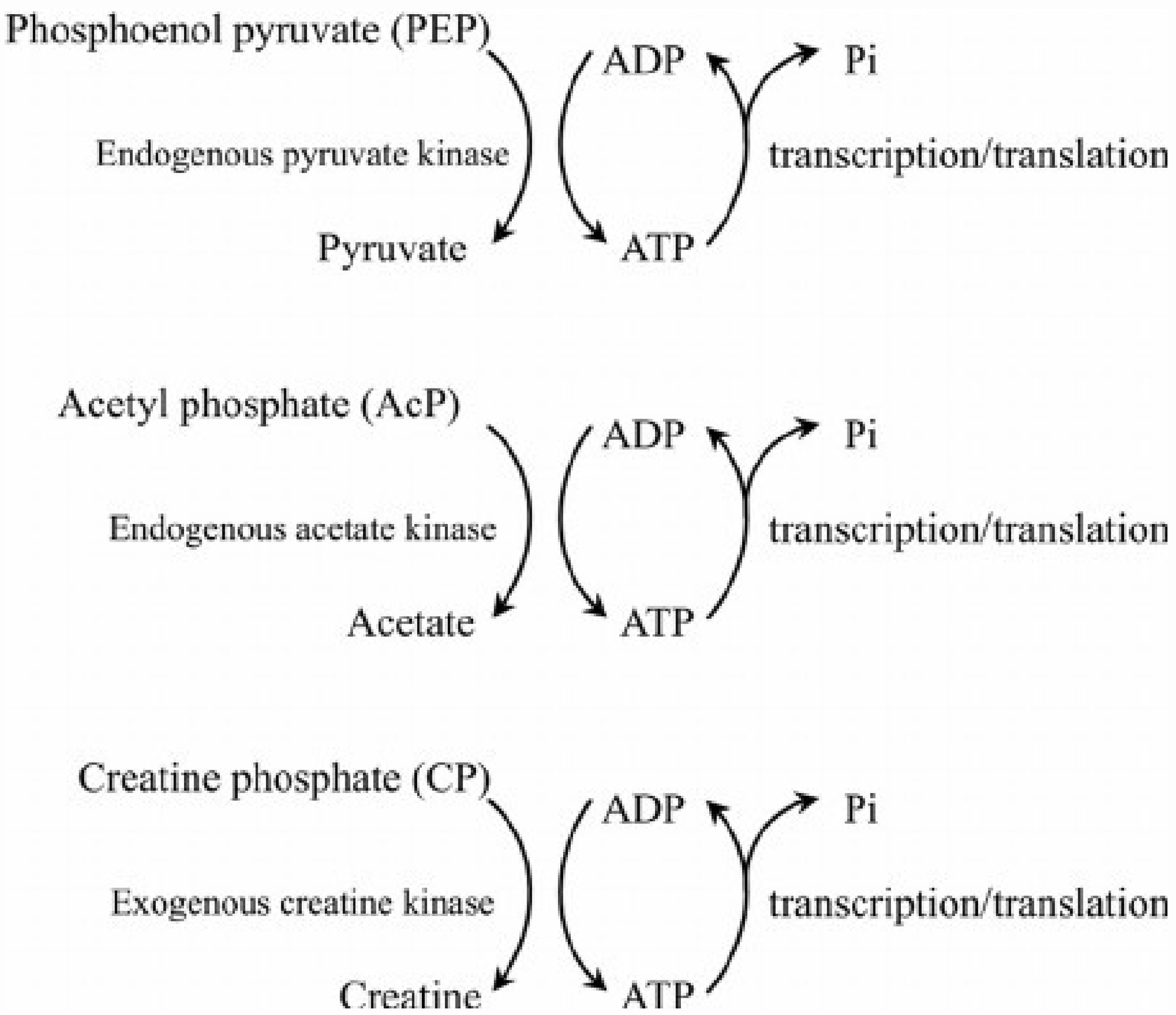
NADH and $FADH_2$ transfer their electrons to the respiratory chain.

The energy released during electron transfer is used to generate a proton gradient across the inner mitochondrial membrane.

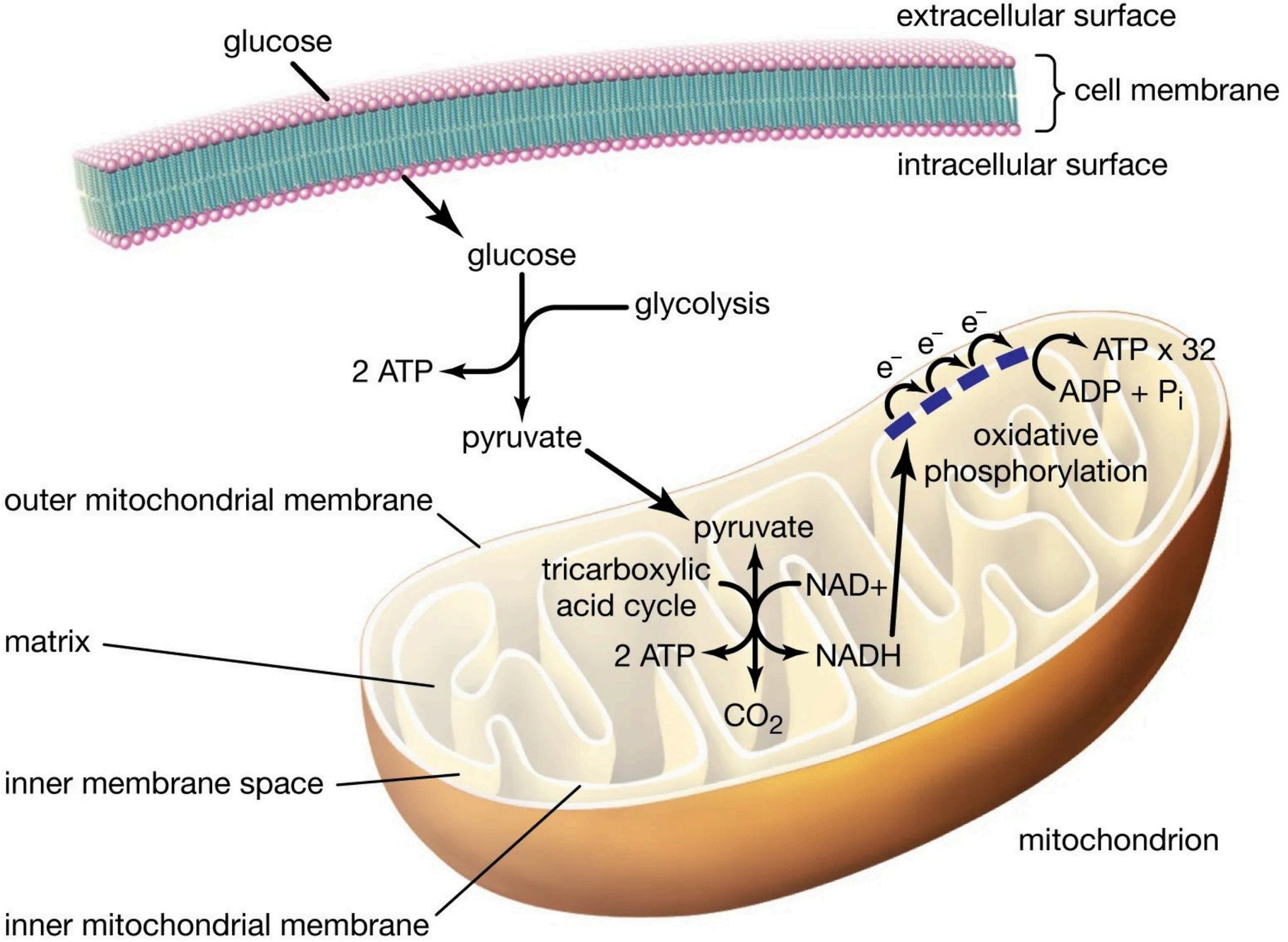
This gradient then provides the energy required for ATP synthesis.

Overall pathway

Nutrients → Biological oxidation → NADH/$FADH_2$ → Respiratory chain → Proton gradient → ATP


Phosphoenol pyruvate (PEP)
Endogenous pyruvate kinase
Pyruvate
ADP
ATP
Pi
transcription/translation
Acetyl phosphate (AcP)
Endogenous acetate kinase
Acetate
ADP
ATP
Pi
transcription/translation
Creatine phosphate (CP)
Exogenous creatine kinase
Creatine
ADP
ATP
Pi
transcription/translation

Basic overview of processes of ATP production



Student task

Task 1 – check your understanding :

1. What is bioenergetics, and what does it study?
2. Why do cells require a continuous supply of energy?
3. What is the role of Gibbs free energy in biological reactions?
4. What is the difference between exergonic and endergonic reactions?
5. What is energy coupling?
6. Why is ATP considered the main immediate energy-transfer molecule of the cell?
7. What are the three structural components of ATP?
8. What happens during ATP hydrolysis?
9. Why is ATP hydrolysis an exergonic reaction?
10. Why must ATP be continuously regenerated?

Student task

Task2 Completethe ATPcycle

Complete the pathway:

$ATP + H_2O \rightarrow$ _____ + _____ + free energy

_____ + Pi + energy → ATP

Then explain:

1. Where does the energy for ATP regeneration come from?
2. Why can ATP be described as a recyclable energy-transfer molecule?

Conclusion

Bioenergetics explainshowcellstransform energy from nutrients into usable forms.

ATP couples energy-releasing reactions to biosynthesis, active transport and mechanical work.

ATP hydrolysis releases free energy under cellular conditions. Cells continuously regenerate ATP from ADP and inorganic phosphate.

NADH and FADH2 carry electrons from nutrient oxidation to the respiratory chain.

Electron transfer generates a proton gradient. ATP synthase uses this gradient to produce ATP during oxidative phosphorylation.

References

1. Nelson, D. L., & Cox, M. M. Lehninger Principles of Biochemistry. W.H. Freeman / Macmillan Learning.
2. Berg, J. M., Tymoczko, J. L., Gatto, G. J., & Stryer, L. Biochemistry. W.H. Freeman.
3. Alberts, B. et al. Molecular Biology of the Cell. Garland Science.
4. Cooper, G. M., & Hausman, R. E. The Cell: A Molecular Approach. Oxford University Press.
5. Voet, D., Voet, J. G., & Pratt, C. W. Fundamentals of Biochemistry: Life at the Molecular Level. Wiley.
6. OpenStax Biology 2e. Energy and Metabolism.
7. OpenStax Biology 2e. ATP: Adenosine Triphosphate.
8. NCBI Bookshelf. Biochemistry.