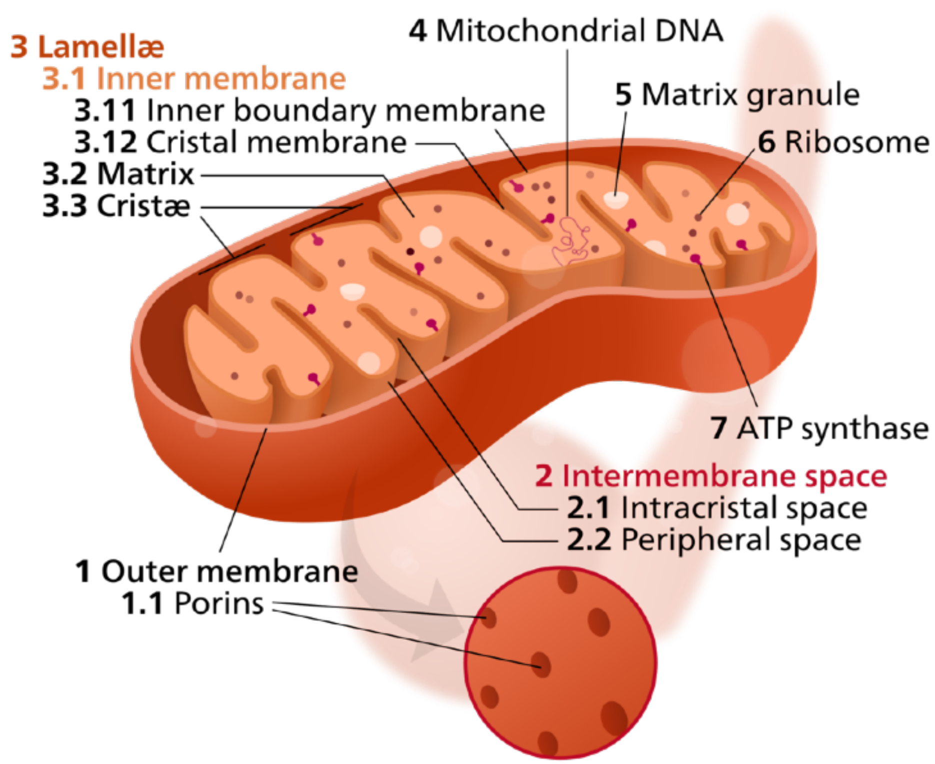
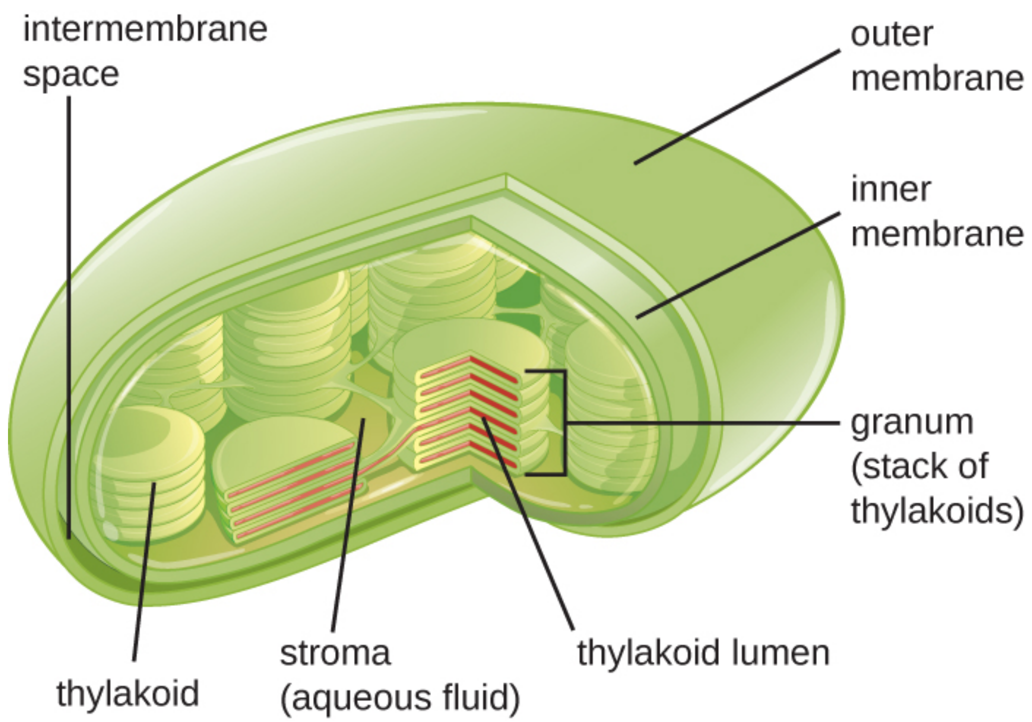
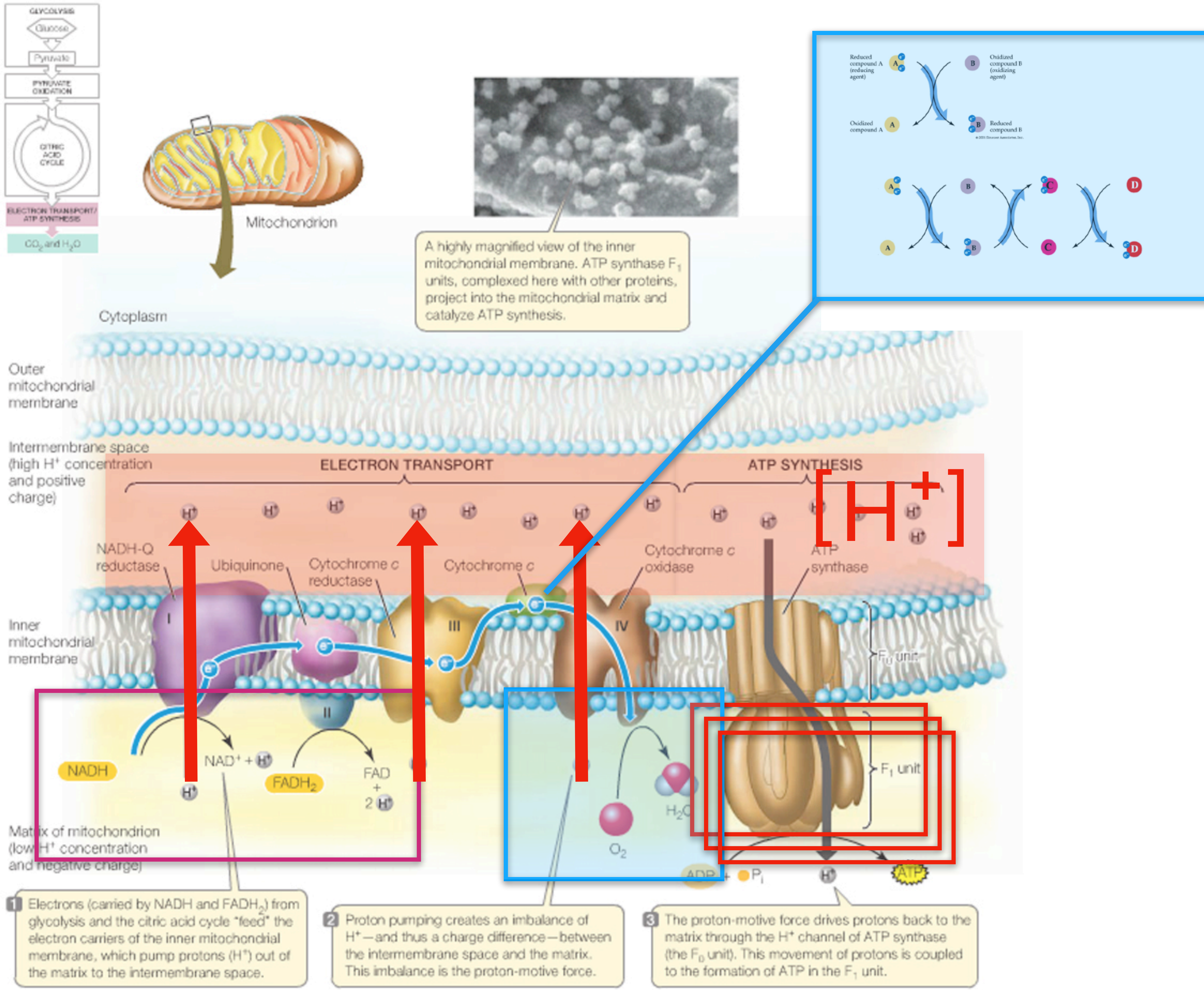
BIOL2107, Fall ’23

Lecture 21

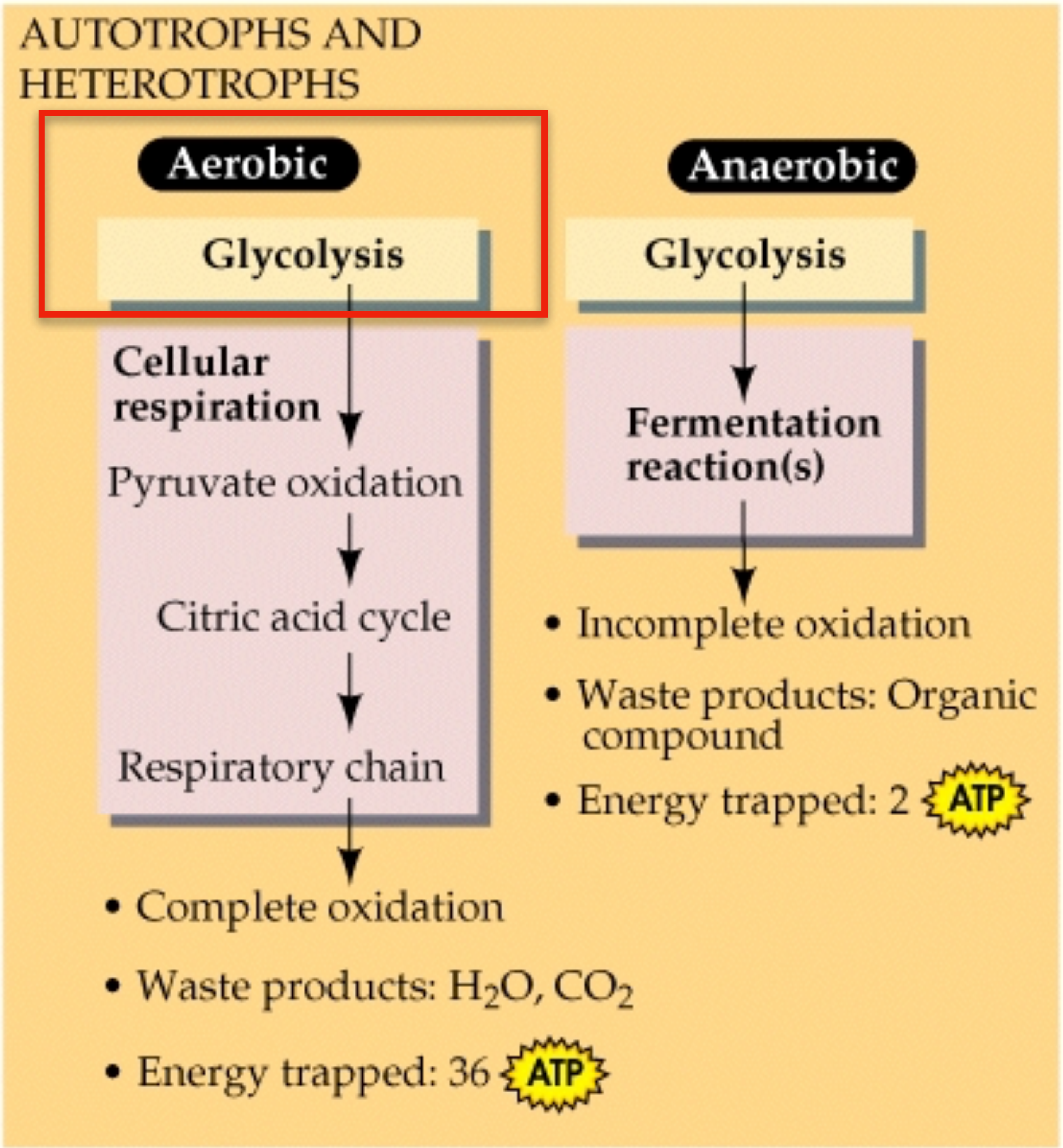


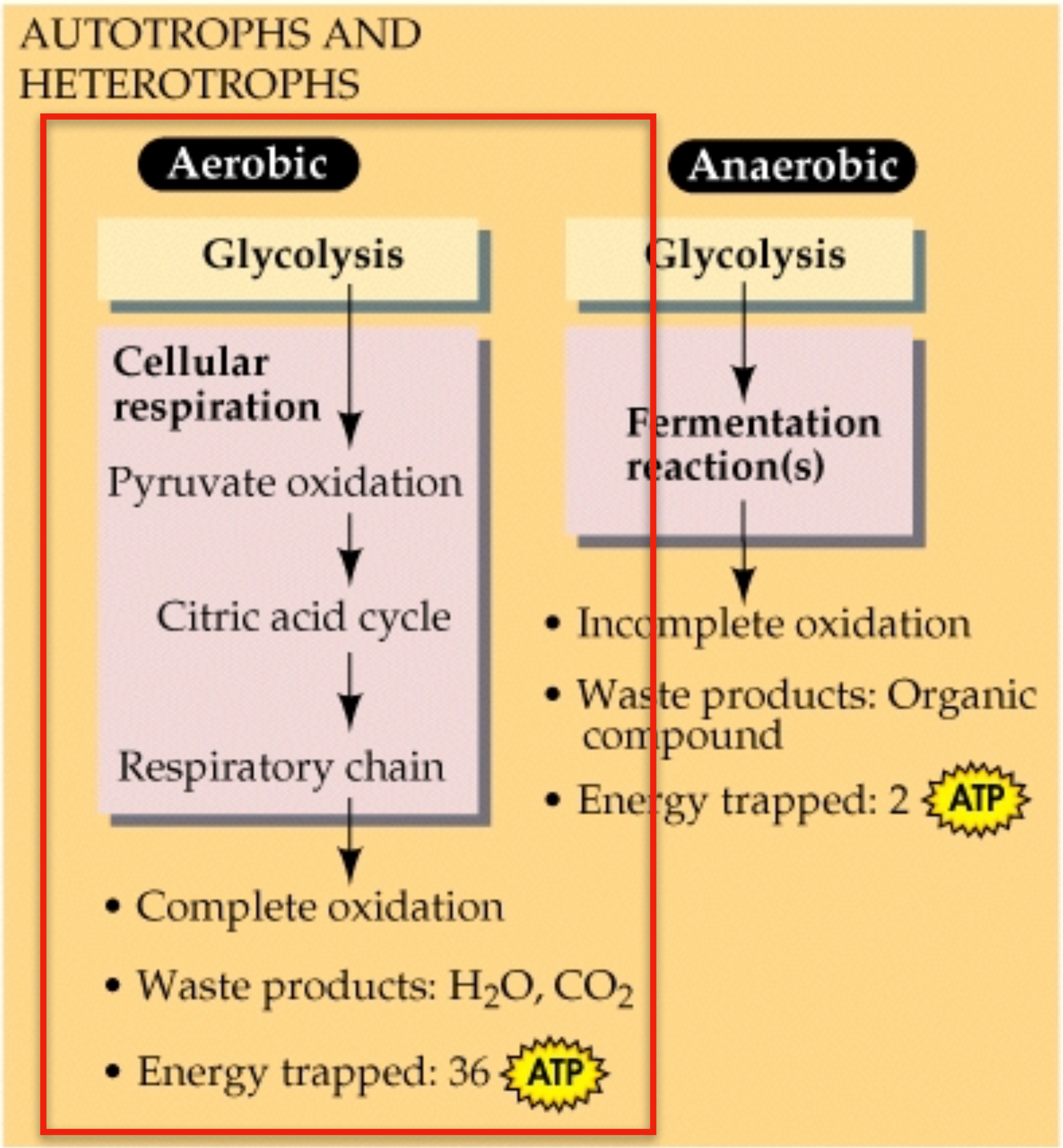


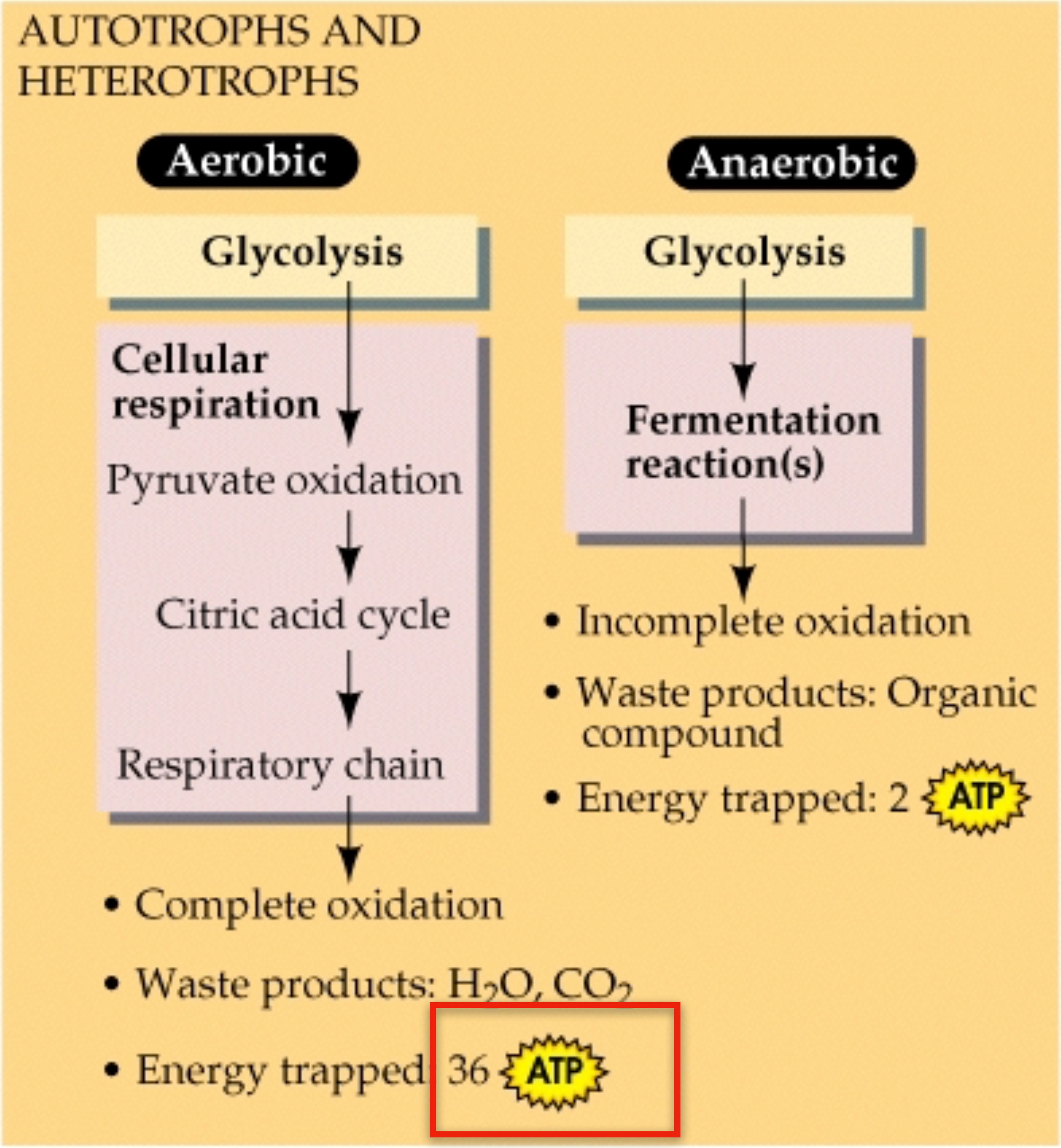
Carbon Metabolism -Respiration / Photosynthesis

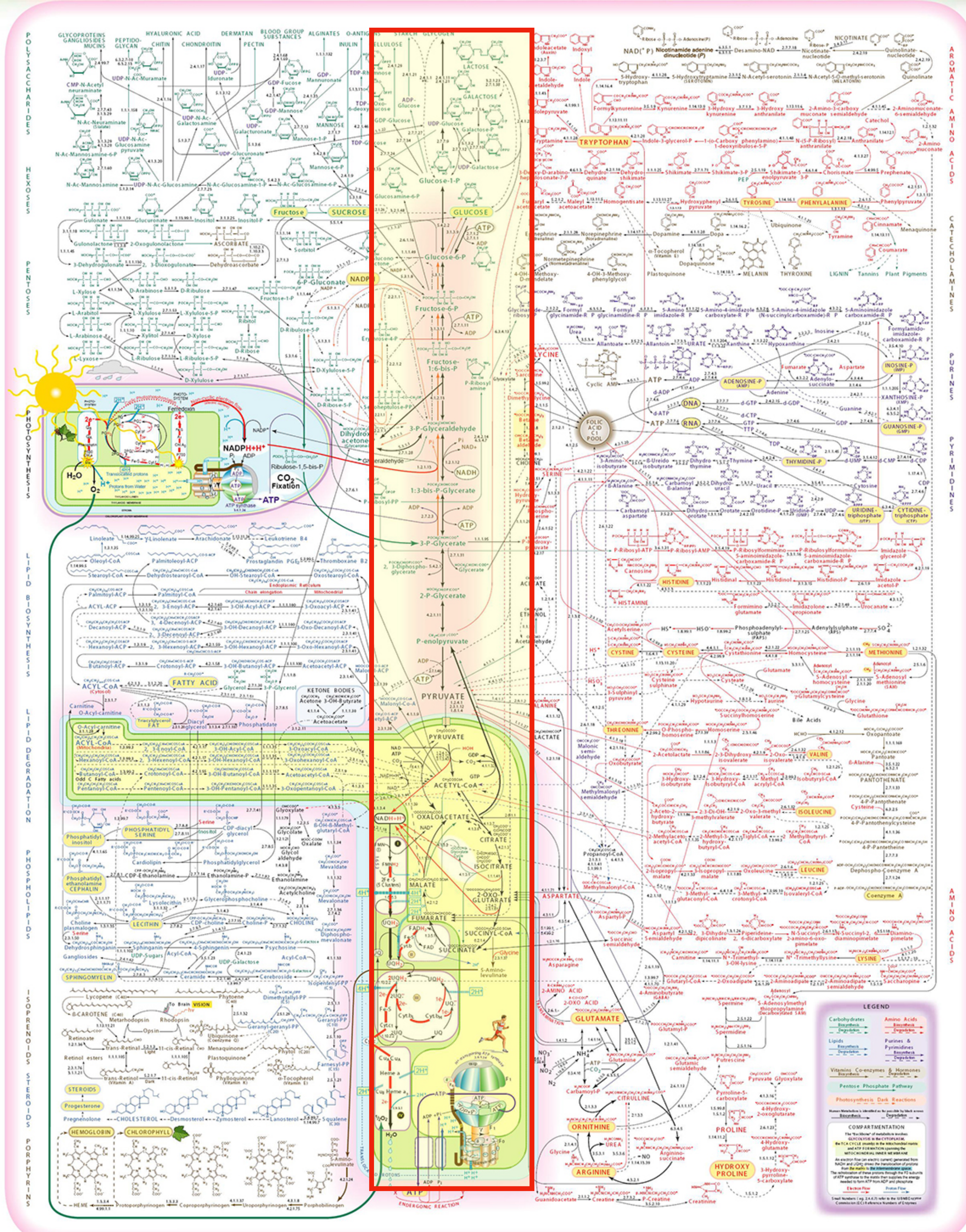


GLYCOLYSIS
Glucose
Pyruvate
PYRUVATE OXIDATION
CITRIC ACID CYCLE
ELECTRON TRANSPORT/ ATP SYNTHESIS
CO_2 and H_2O
Mitochondrion
A highly magnified view of the inner mitochondrial membrane. ATP synthase F_1 units, complexed here with other proteins, project into the mitochondrial matrix and catalyze ATP synthesis.
Reduced compound A (reducing agent)
Oxidized compound B (oxidizing agent)
Oxidized compound A
Reduced compound B
Cytoplasm
Outer mitochondrial membrane
Intermembrane space (high H^+ concentration and positive charge)
ELECTRON TRANSPORT
ATP SYNTHESIS
$[H^+]$
NADH-Q reductase
Ubiquinone
Cytochrome c reductase
Cytochrome c
Cytochrome c oxidase
ATP synthase
I
II
III
IV
Inner mitochondrial membrane
F_0 unit
F_1 unit
NADH
$NAD^+ + H^+$
$FADH_2$
FAD + 2 H^+
O_2
H_2O
ADP + P_i
ATP
Matrix of mitochondrion (low H^+ concentration and negative charge)
1 Electrons (carried by NADH and $FADH_2$) from glycolysis and the citric acid cycle "feed" the electron carriers of the inner mitochondrial membrane, which pump protons (H^+) out of the matrix to the intermembrane space.
2 Proton pumping creates an imbalance of H^+—and thus a charge difference—between the intermembrane space and the matrix. This imbalance is the proton-motive force.
3 The proton-motive force drives protons back to the matrix through the H^+ channel of ATP synthase (the F_0 unit). This movement of protons is coupled to the formation of ATP in the F_1 unit.

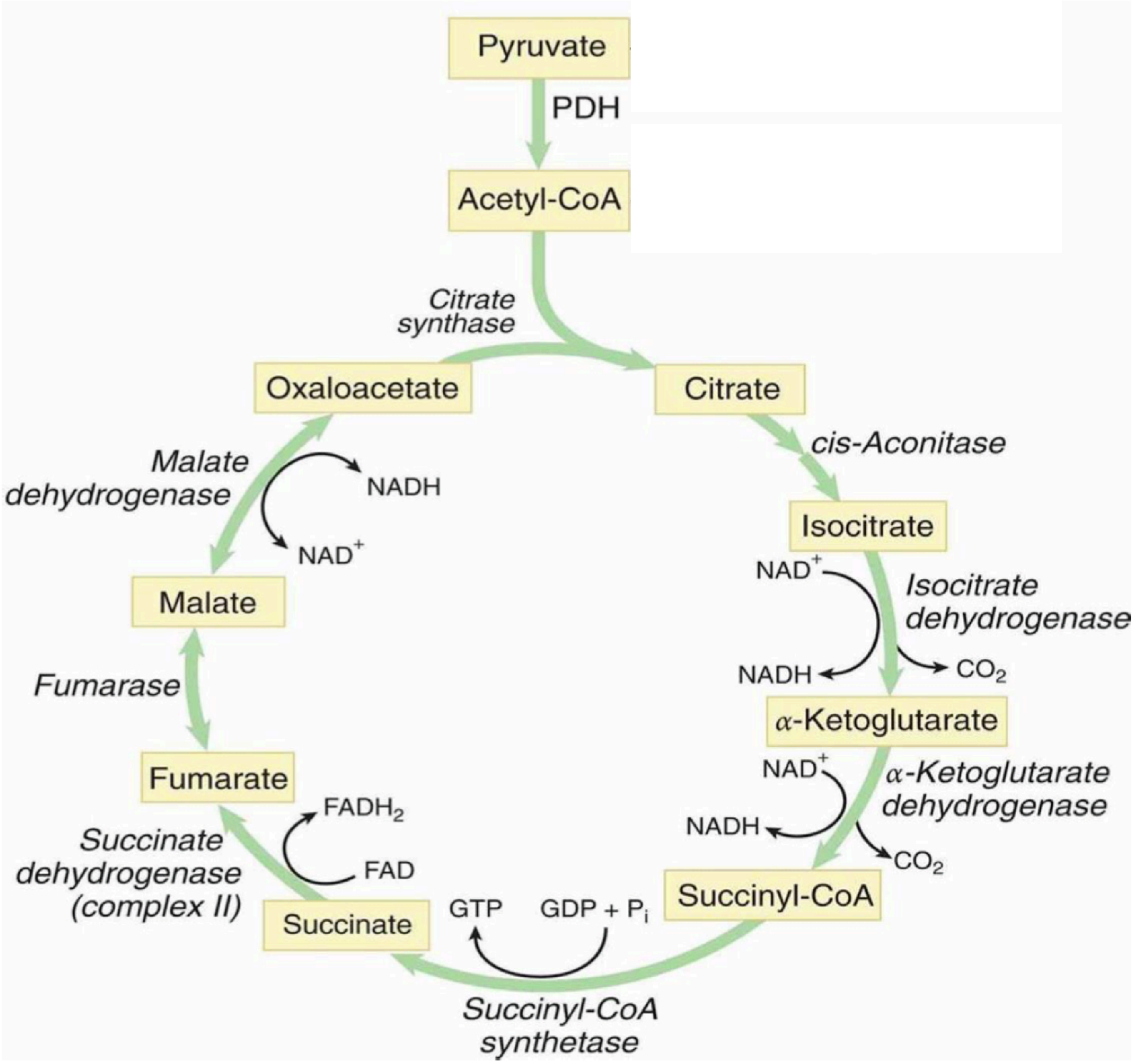

AUTOTROPHS AND HETEROTROPHS
Aerobic
Glycolysis
Cellular respiration
Pyruvate oxidation
Citric acid cycle
Respiratory chain
• Complete oxidation
• Waste products: H_2O, CO_2
• Energy trapped: 36 ATP
Anaerobic
Glycolysis
Fermentation reaction(s)
• Incomplete oxidation
• Waste products: Organic compound
• Energy trapped: 2 ATP


AUTOTROPHS AND HETEROTROPHS
Aerobic
Glycolysis
Cellular respiration
Pyruvate oxidation
Citric acid cycle
Respiratory chain
• Complete oxidation
• Waste products: H_2O, CO_2
• Energy trapped: 36 ATP
Anaerobic
Glycolysis
Fermentation reaction(s)
• Incomplete oxidation
• Waste products: Organic compound
• Energy trapped: 2 ATP

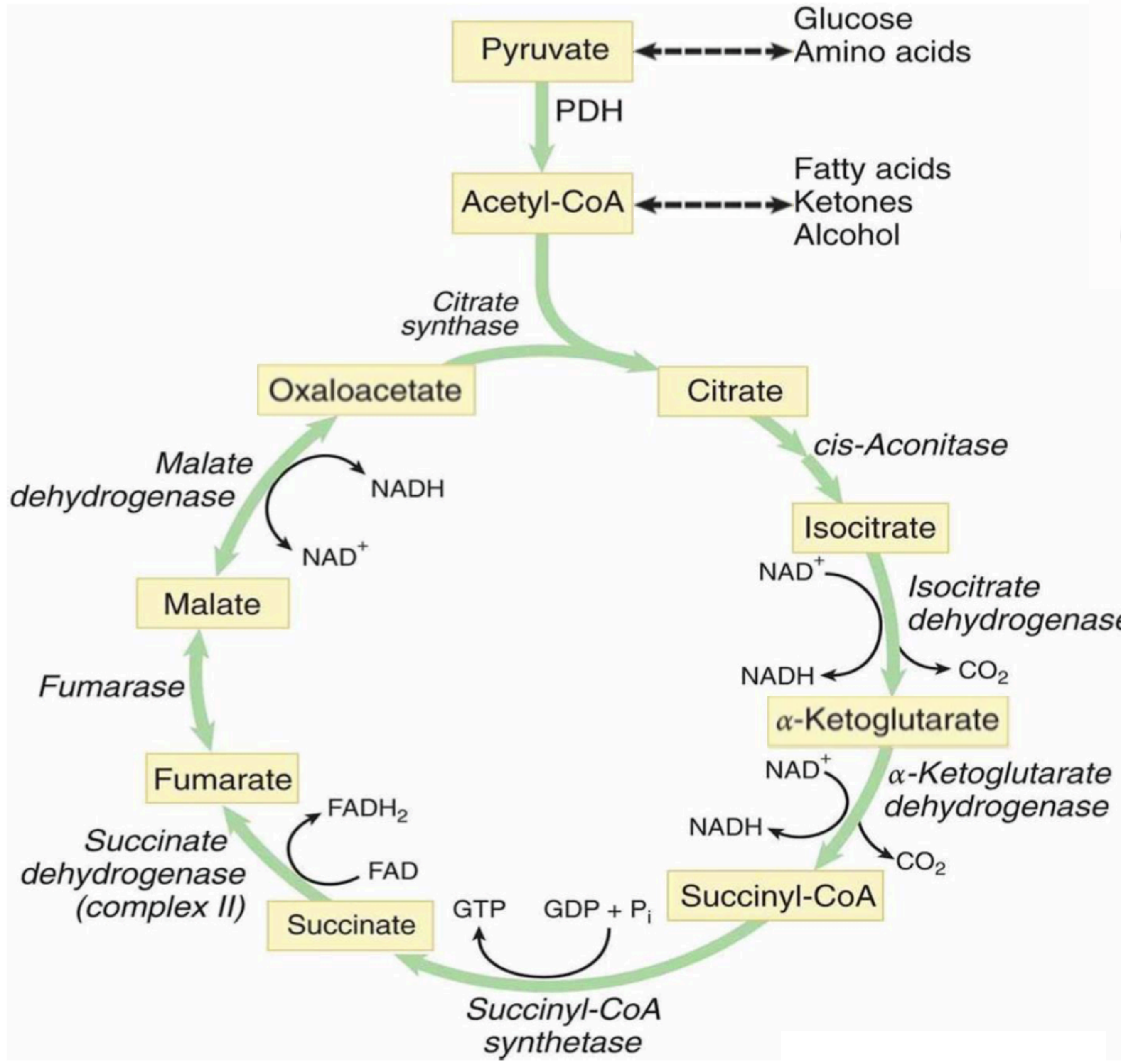

AUTOTROPHS AND HETEROTROPHS
Aerobic
Anaerobic
Glycolysis
Glycolysis
Cellular respiration
Pyruvate oxidation
Citric acid cycle
Respiratory chain
Fermentation reaction(s)
• Incomplete oxidation
• Waste products: Organic compound
• Energy trapped: 2 ATP
• Complete oxidation
• Waste products: H_2O, CO_2
• Energy trapped 36 ATP

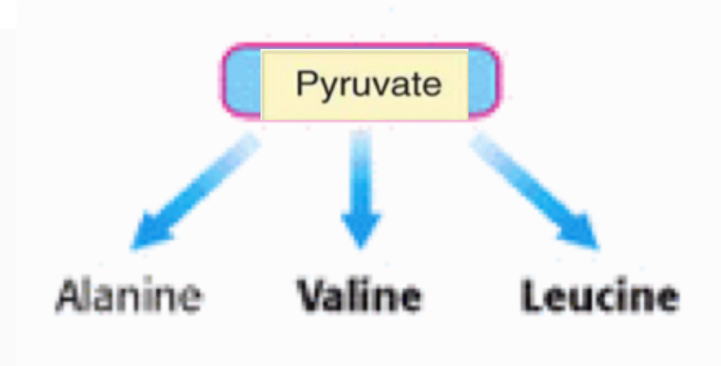


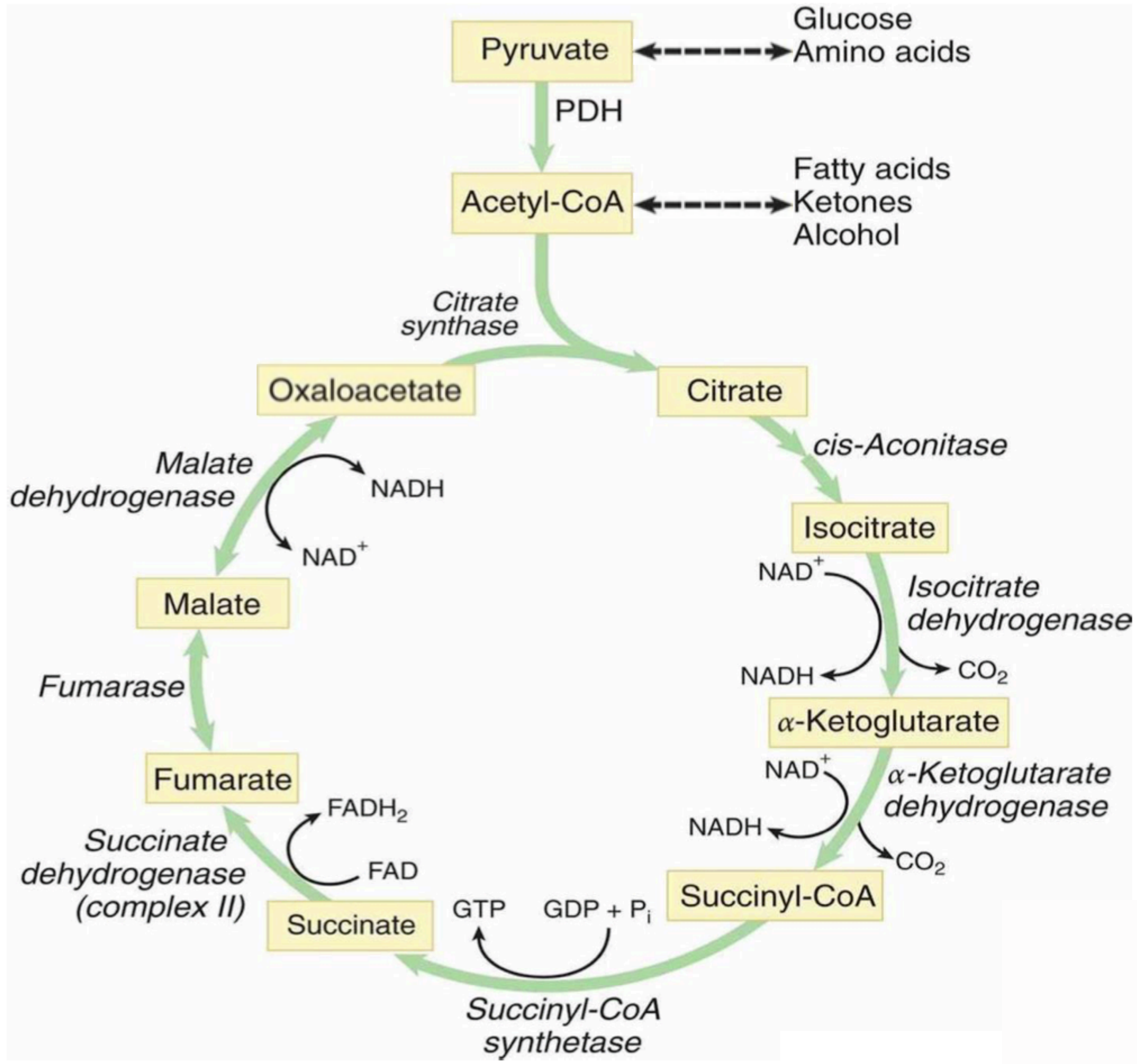
TRYPTOPHAN
TYROSINE
PHENYLALANINE
Fructose
SUCROSE
GLUCOSE
Glucose-1-P
Glucose-6-P
Fructose-6-P
Fructose-1:6-bis-P
3-P-Glyceraldehyde
1:3-bis-P-Glycerate
3-P-Glycerate
2-P-Glycerate
P-enolpyruvate
PYRUVATE
ACETYL-CoA
OXALOACETATE
CITRATE
ISOCITRATE
2-OXO GLUTARATE
SUCCINYL-CoA
SUCCINATE
FUMARATE
MALATE
FATTY ACID
ACYL-CoA
GLUTAMATE
ASPARTATE
ORNITHINE
ARGININE
PROLINE
HYDROXY PROLINE
HISTIDINE
METHIONINE
CYSTEINE
VALINE
LEUCINE
ISOLEUCINE
LYSINE
DNA
RNA
FOLIC ACID C1 POOL
LECITHIN
CHOLINE
STEROIDS
CHOLESTEROL
HEMOGLOBIN
CHLOROPHYLL
CO2 Fixation
ATP
LEGEND
COMPARTMENTATION

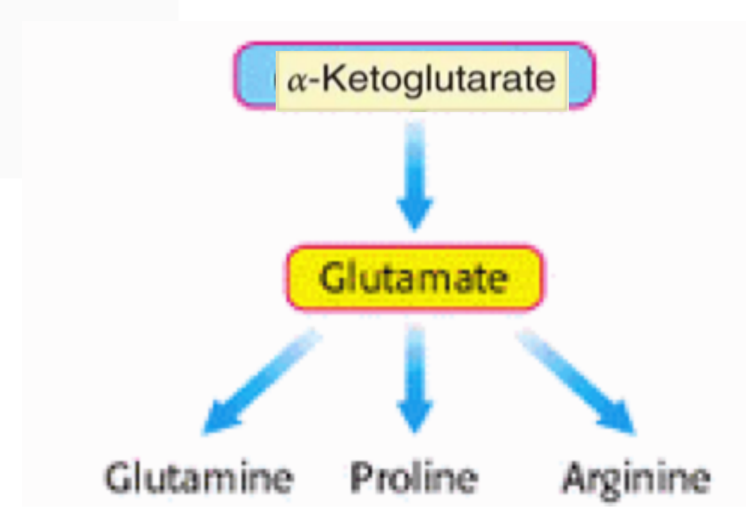


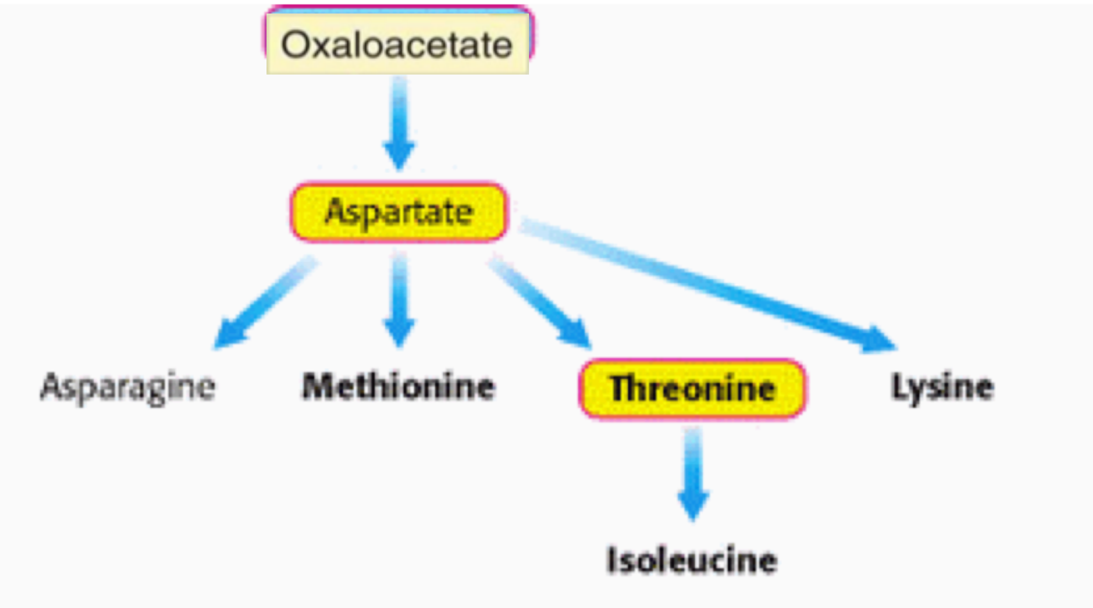
Pyruvate
PDH
Acetyl-CoA
Citrate synthase
Oxaloacetate
Citrate
cis-Aconitase
Malate dehydrogenase
NADH
NAD+
Isocitrate
NAD+
Isocitrate dehydrogenase
Malate
NADH
CO2
Fumarase
α-Ketoglutarate
NAD+
α-Ketoglutarate dehydrogenase
Fumarate
FADH2
NADH
Succinate dehydrogenase (complex II)
FAD
CO2
Succinyl-CoA
GTP
GDP + Pi
Succinate
Succinyl-CoA synthetase

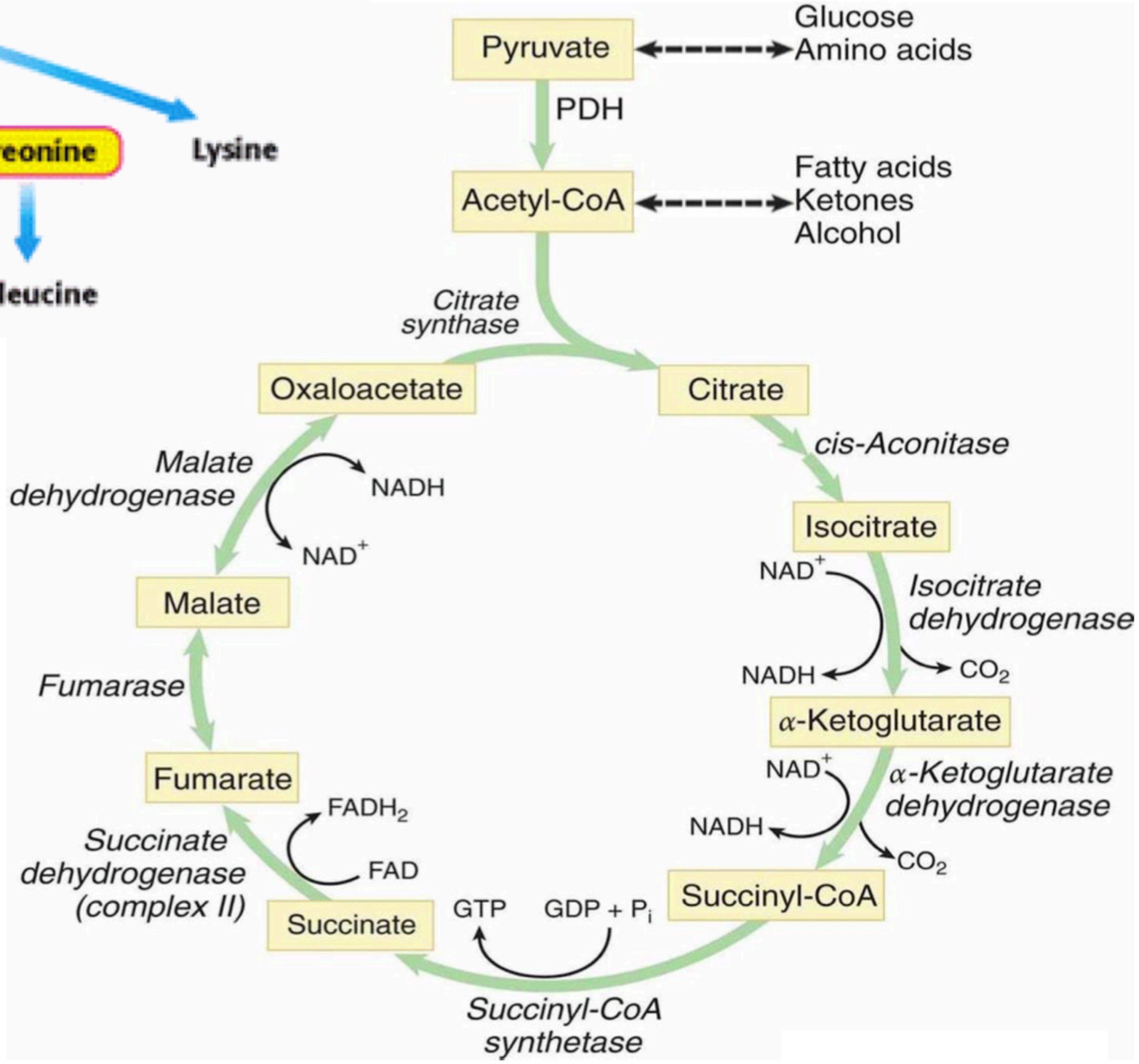

Pyruvate
Glucose
Amino acids
PDH
Acetyl-CoA
Fatty acids
Ketones
Alcohol
Citrate synthase
Oxaloacetate
Citrate
cis-Aconitase
Isocitrate
NAD+
Isocitrate dehydrogenase
NADH
CO2
α-Ketoglutarate
NAD+
α-Ketoglutarate dehydrogenase
NADH
CO2
Succinyl-CoA
GTP
GDP + Pi
Succinyl-CoA synthetase
Succinate
FAD
FADH2
Succinate dehydrogenase (complex II)
Fumarate
Fumarase
Malate
NAD+
NADH
Malate dehydrogenase

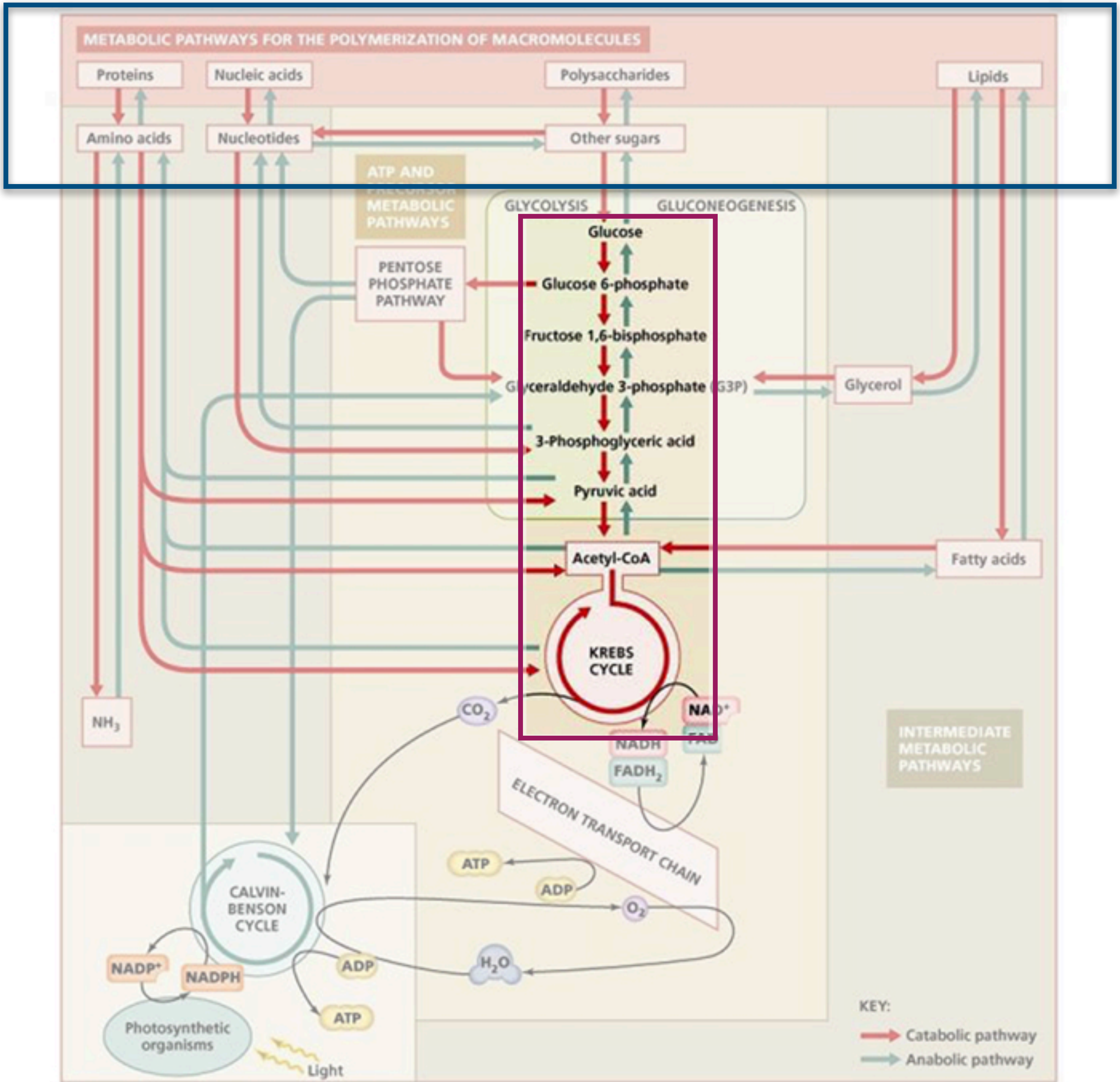

Pyruvate
Alanine
Valine
Leucine


Pyruvate
Glucose
Amino acids
PDH
Acetyl-CoA
Fatty acids
Ketones
Alcohol
Citrate
synthase
Oxaloacetate
Citrate
cis-Aconitase
Malate
dehydrogenase
NADH
NAD^+
Isocitrate
NAD^+
Isocitrate
dehydrogenase
Malate
Fumarase
NADH
CO_2
α-Ketoglutarate
NAD^+
α-Ketoglutarate
dehydrogenase
Fumarate
$FADH_2$
NADH
Succinate
dehydrogenase
(complex II)
FAD
CO_2
Succinyl-CoA
Succinate
GTP
GDP + P_i
Succinyl-CoA
synthetase


α-Ketoglutarate
Glutamate
Glutamine
Proline
Arginine


Oxaloacetate
Aspartate
Asparagine
Methionine
Threonine
Lysine
Isoleucine


Pyruvate
Glucose
Amino acids
PDH
Acetyl-CoA
Fatty acids
Ketones
Alcohol
Citrate synthase
Oxaloacetate
Citrate
cis-Aconitase
Isocitrate
NAD+
NADH
Isocitrate dehydrogenase
CO2
α-Ketoglutarate
NAD+
NADH
α-Ketoglutarate dehydrogenase
CO2
Succinyl-CoA
GTP
GDP + Pi
Succinyl-CoA synthetase
Succinate
FADH2
FAD
Succinate dehydrogenase (complex II)
Fumarate
Fumarase
Malate
Malate dehydrogenase
NADH
NAD+

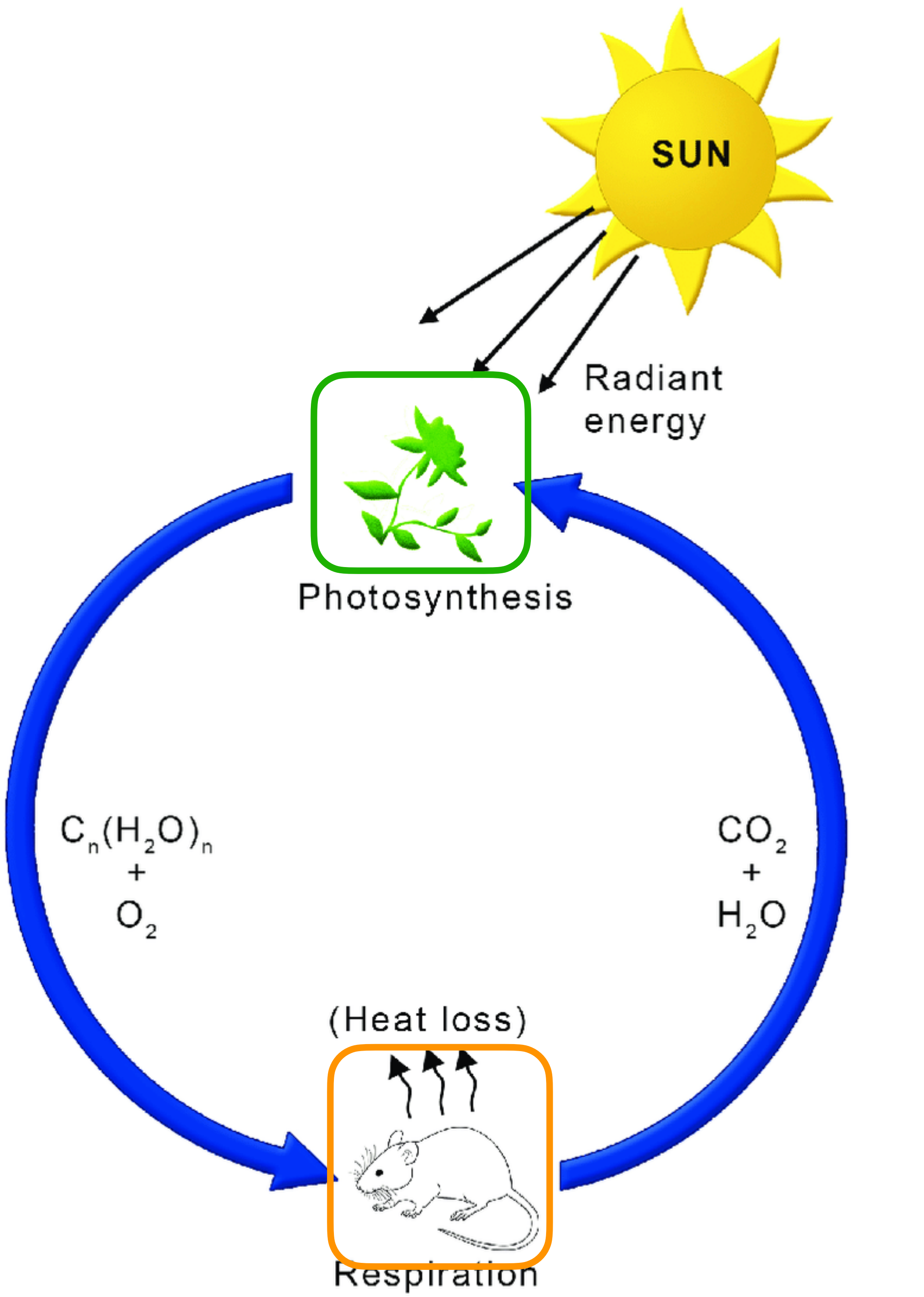

METABOLIC PATHWAYS FOR THE POLYMERIZATION OF MACROMOLECULES
Proteins
Nucleic acids
Polysaccharides
Lipids
Amino acids
Nucleotides
Other sugars
ATP AND PRECURSOR METABOLIC PATHWAYS
GLYCOLYSIS
GLUCONEOGENESIS
Glucose
PENTOSE PHOSPHATE PATHWAY
Glucose 6-phosphate
Fructose 1,6-bisphosphate
Glyceraldehyde 3-phosphate (G3P)
Glycerol
3-Phosphoglyceric acid
Pyruvic acid
Acetyl-CoA
Fatty acids
KREBS CYCLE
NH_3
CO_2
NADH
$FADH_2$
INTERMEDIATE METABOLIC PATHWAYS
ELECTRON TRANSPORT CHAIN
ATP
ADP
O_2
CALVIN-BENSON CYCLE
H_2O
$NADP^+$
NADPH
ADP
ATP
Photosynthetic organisms
Light
KEY:
Catabolic pathway
Anabolic pathway

$C_6H_{12}O_6 + 6\ O_2 \text{--->}\ 6\ CO_2 + 6\ H_2O$ = RESPIRATION

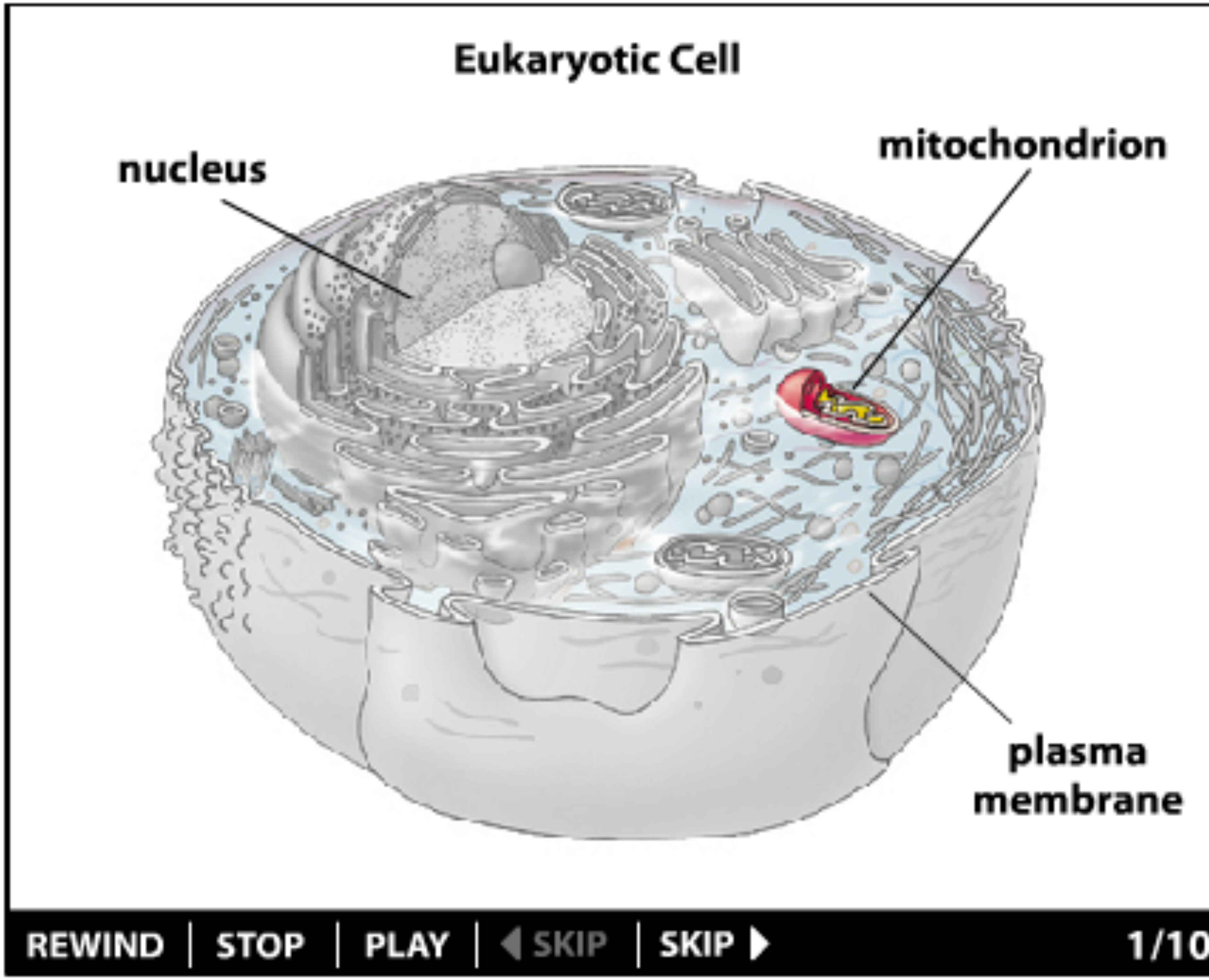
$C_6H_{12}O_6 + 6\ O_2 \text{<---}\ 6\ CO_2 + 6\ H_2O +$ 

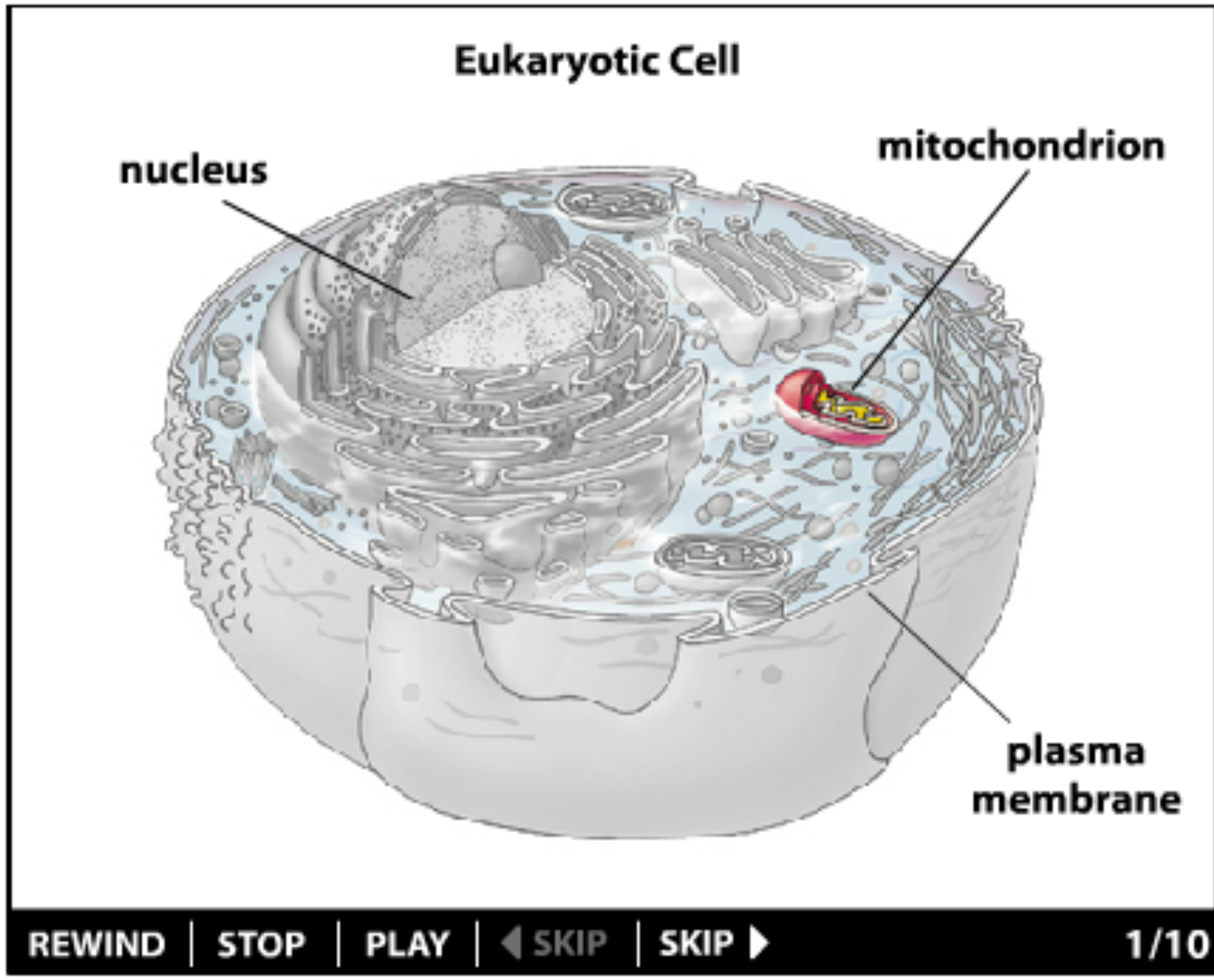
= PHOTOSYNTHESIS

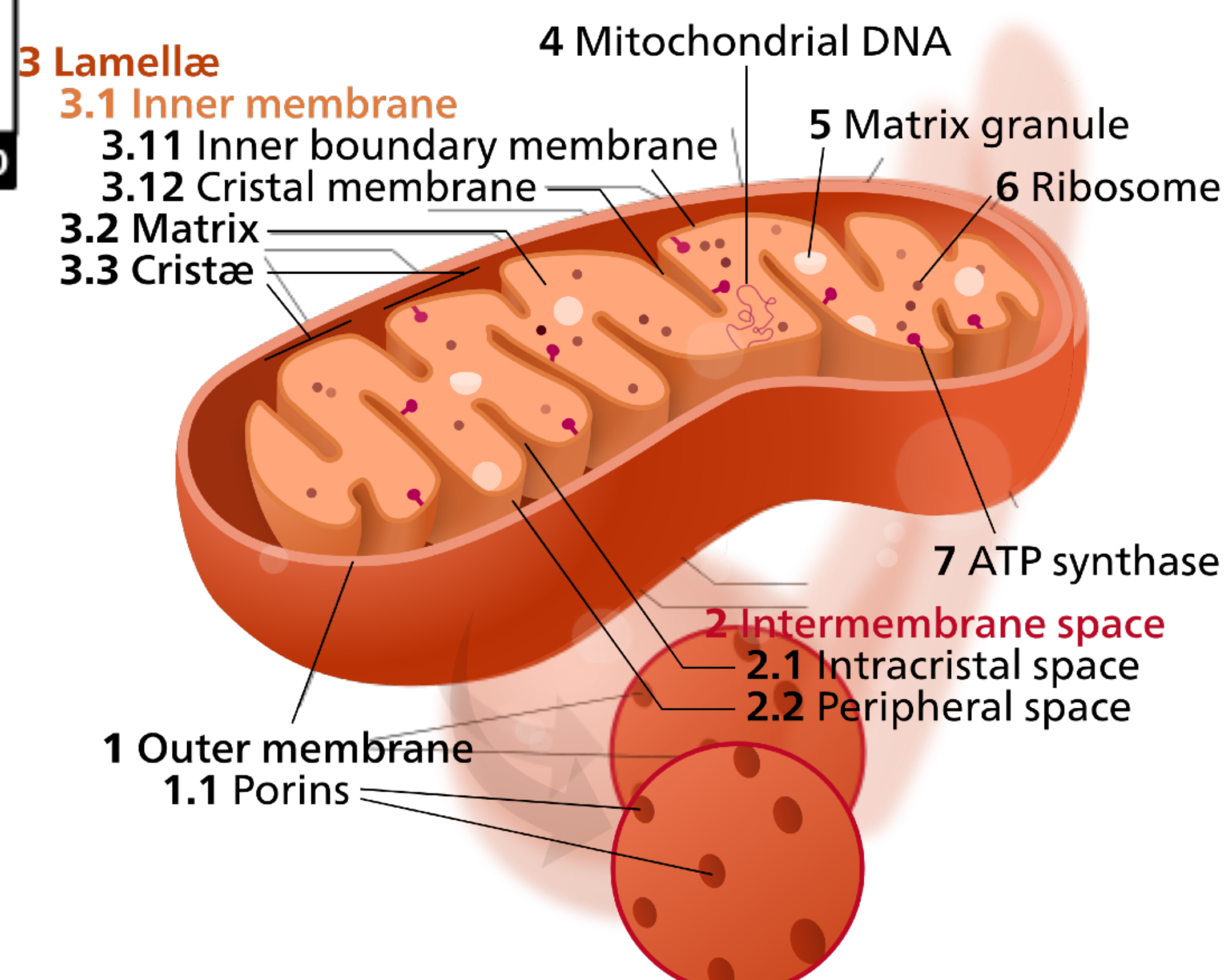
Redox Cycle

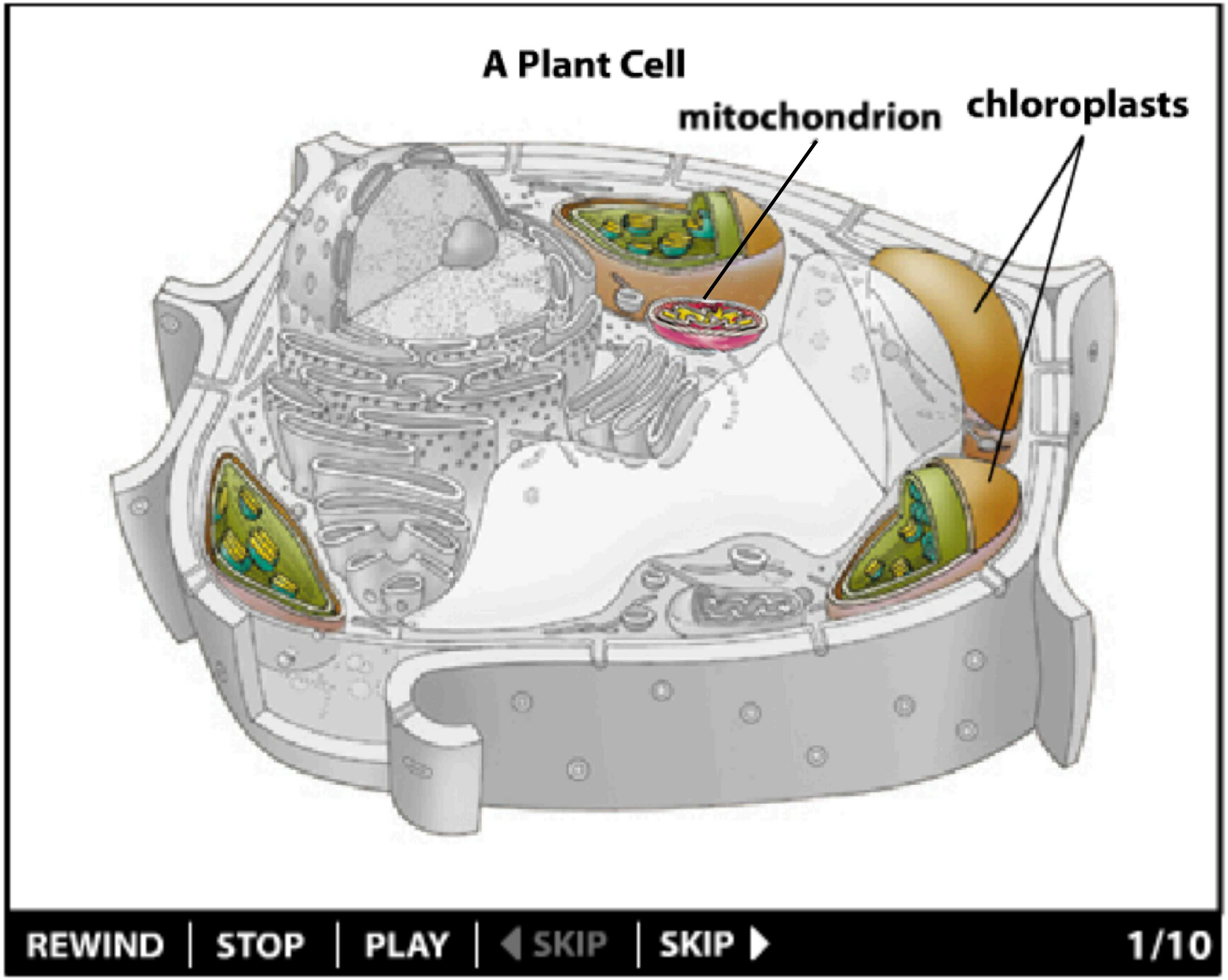


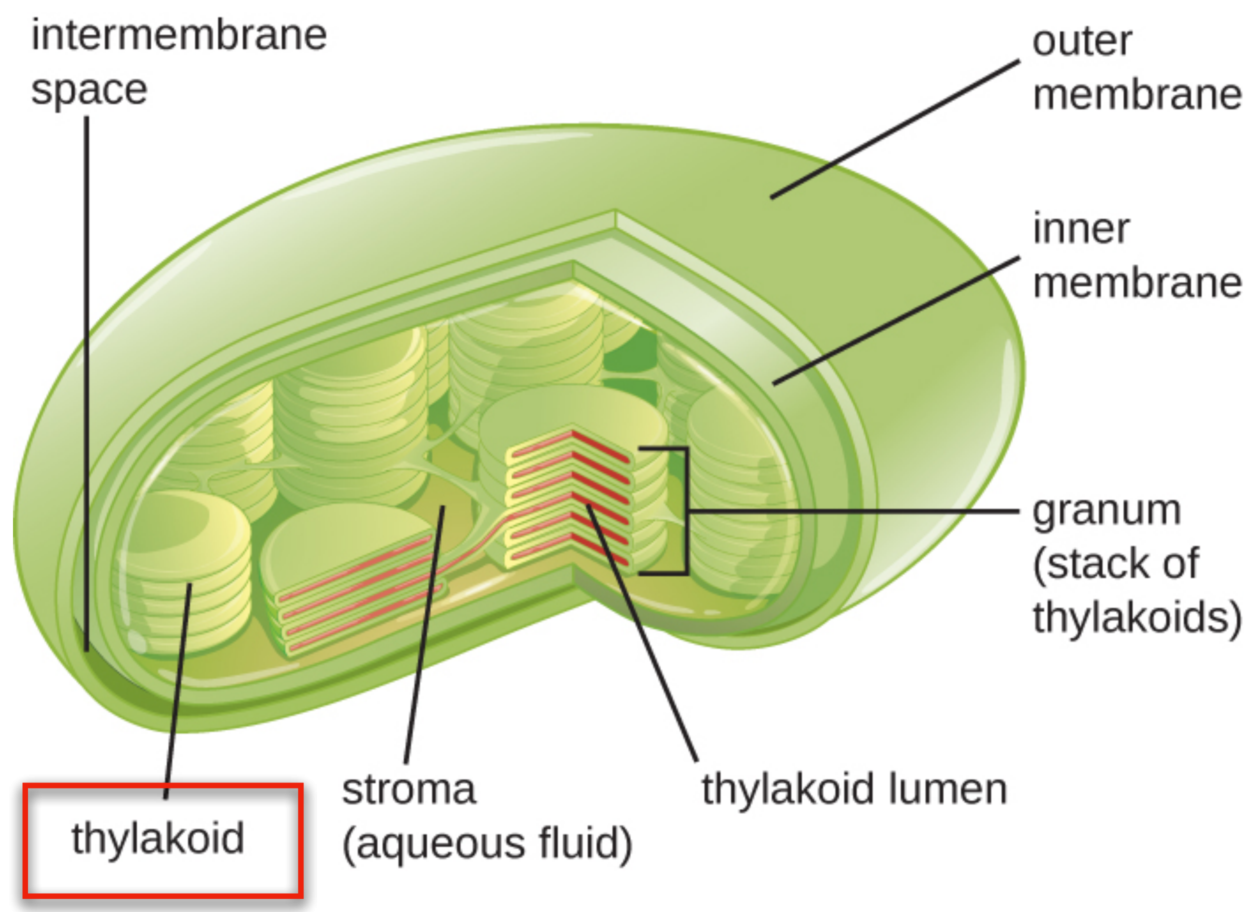
$$C_n(H_2O)_n + O_2 \underset{\text{photosynthesis (reduction)}}{\overset{\text{(oxidation) respiration}}{\rightleftarrows}} CO_2 + H_2O + \Delta E$$

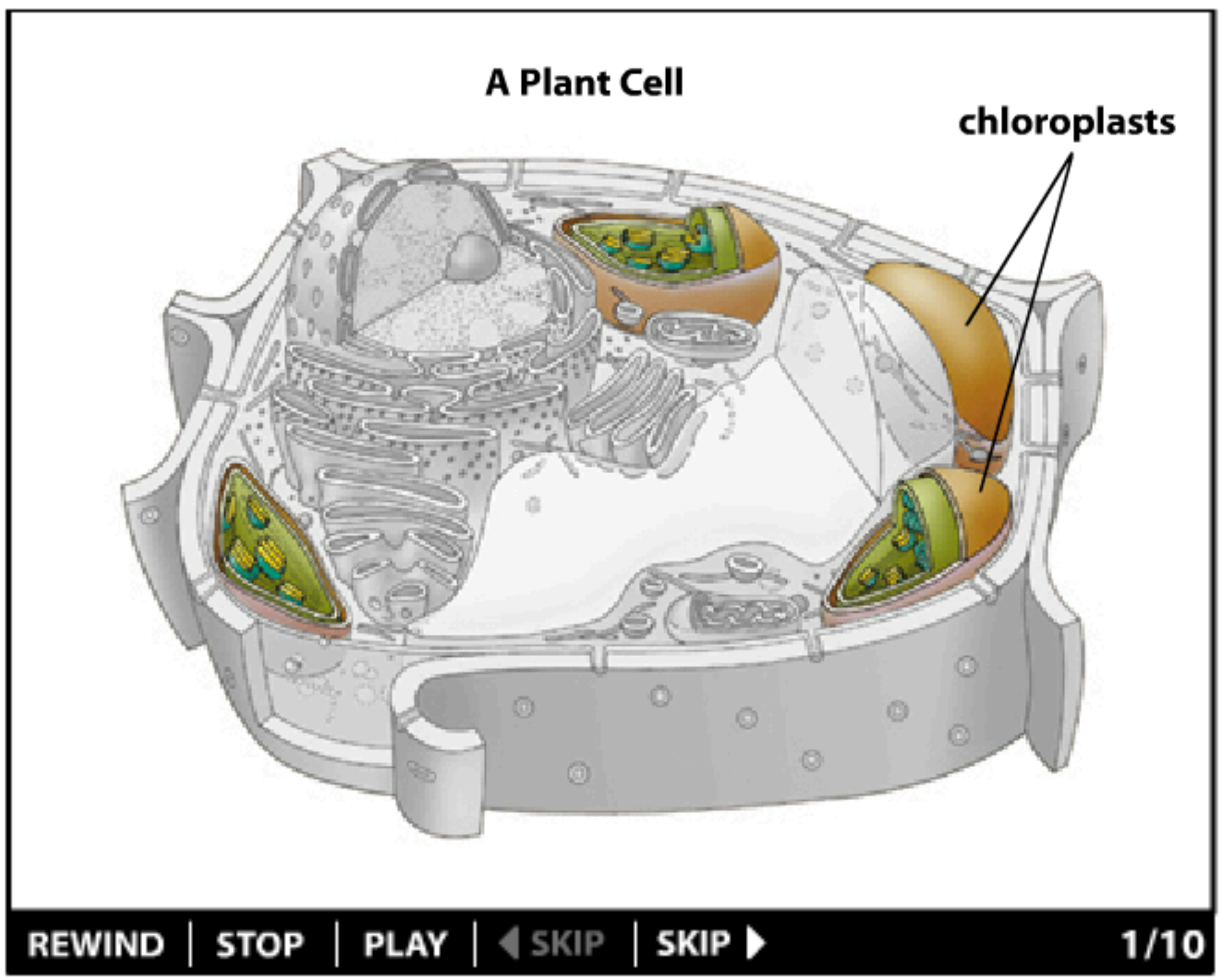

Eukaryotic Cell
nucleus
mitochondrion
plasma membrane
REWIND
STOP
PLAY
SKIP
SKIP
1/10

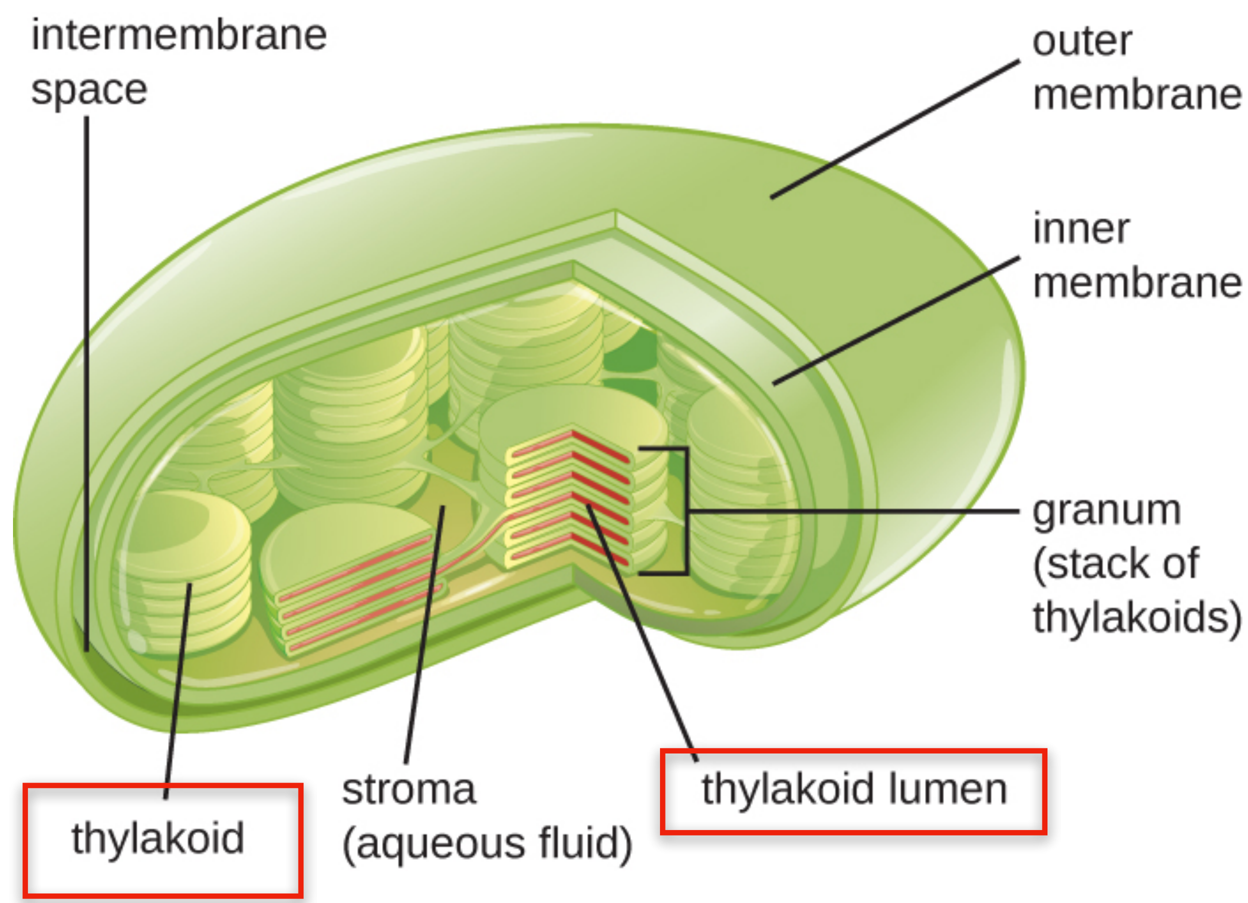

Eukaryotic Cell
nucleus
mitochondrion
plasma membrane
REWIND
STOP
PLAY
SKIP
SKIP
1/10

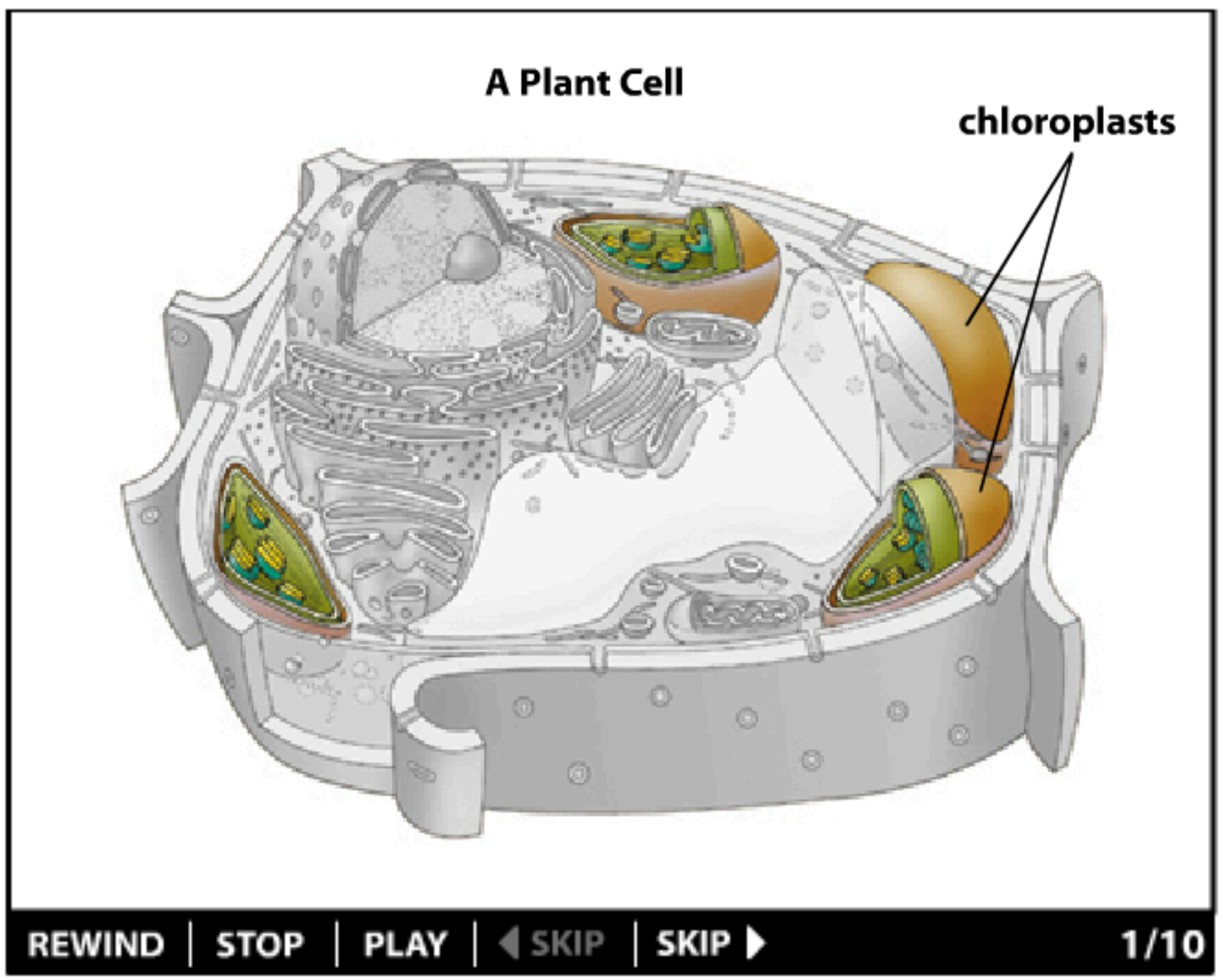

3 Lamellæ
3.1 Inner membrane
3.11 Inner boundary membrane
3.12 Cristal membrane
3.2 Matrix
3.3 Cristæ
4 Mitochondrial DNA
5 Matrix granule
6 Ribosome
7 ATP synthase
2 Intermembrane space
2.1 Intracristal space
2.2 Peripheral space
1 Outer membrane
1.1 Porins


A Plant Cell
mitochondrion
chloroplasts
REWIND
STOP
PLAY
SKIP
SKIP
1/10

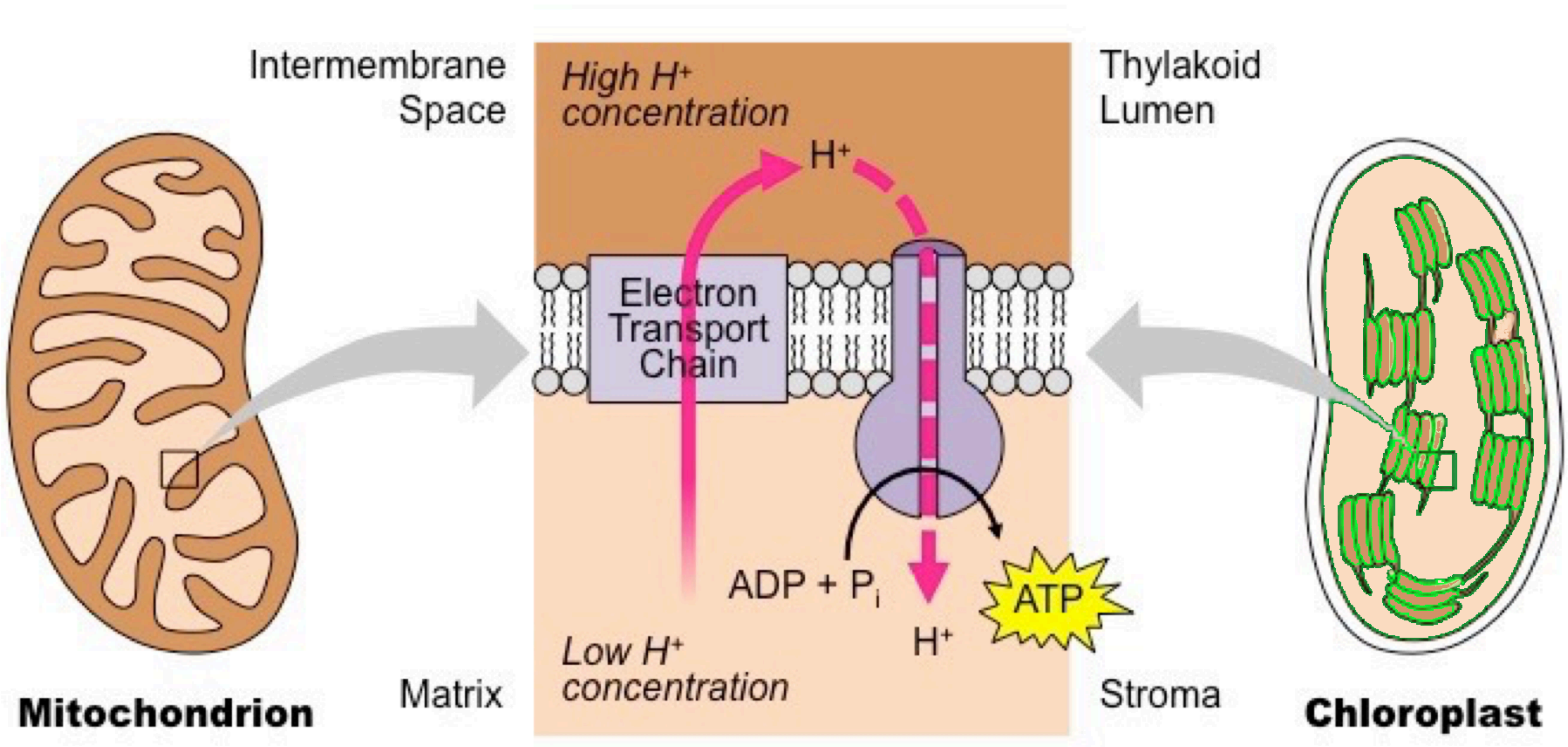

intermembrane space
outer membrane
inner membrane
granum (stack of thylakoids)
thylakoid
stroma (aqueous fluid)
thylakoid lumen


A Plant Cell
chloroplasts
REWIND
STOP
PLAY
SKIP
SKIP
1/10

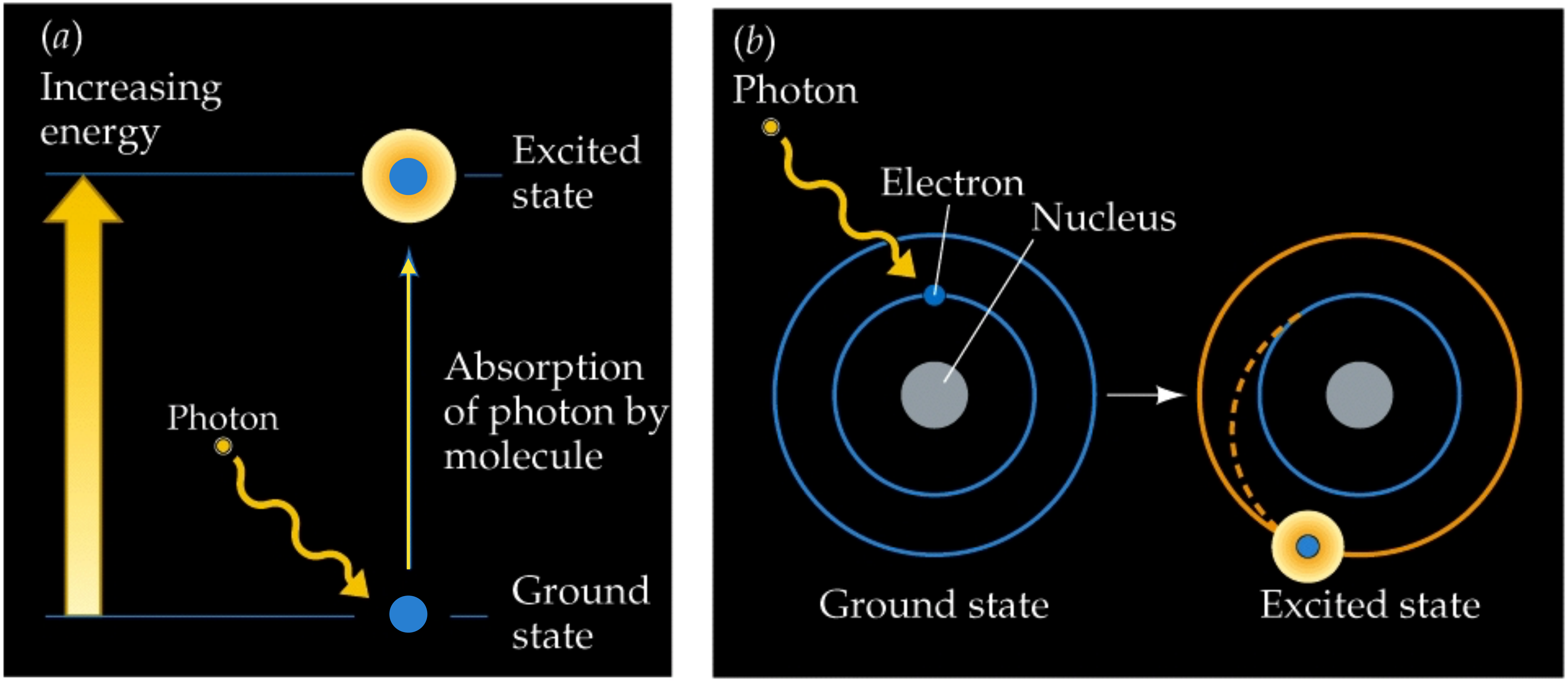

intermembrane space
outer membrane
inner membrane
granum (stack of thylakoids)
thylakoid
stroma (aqueous fluid)
thylakoid lumen

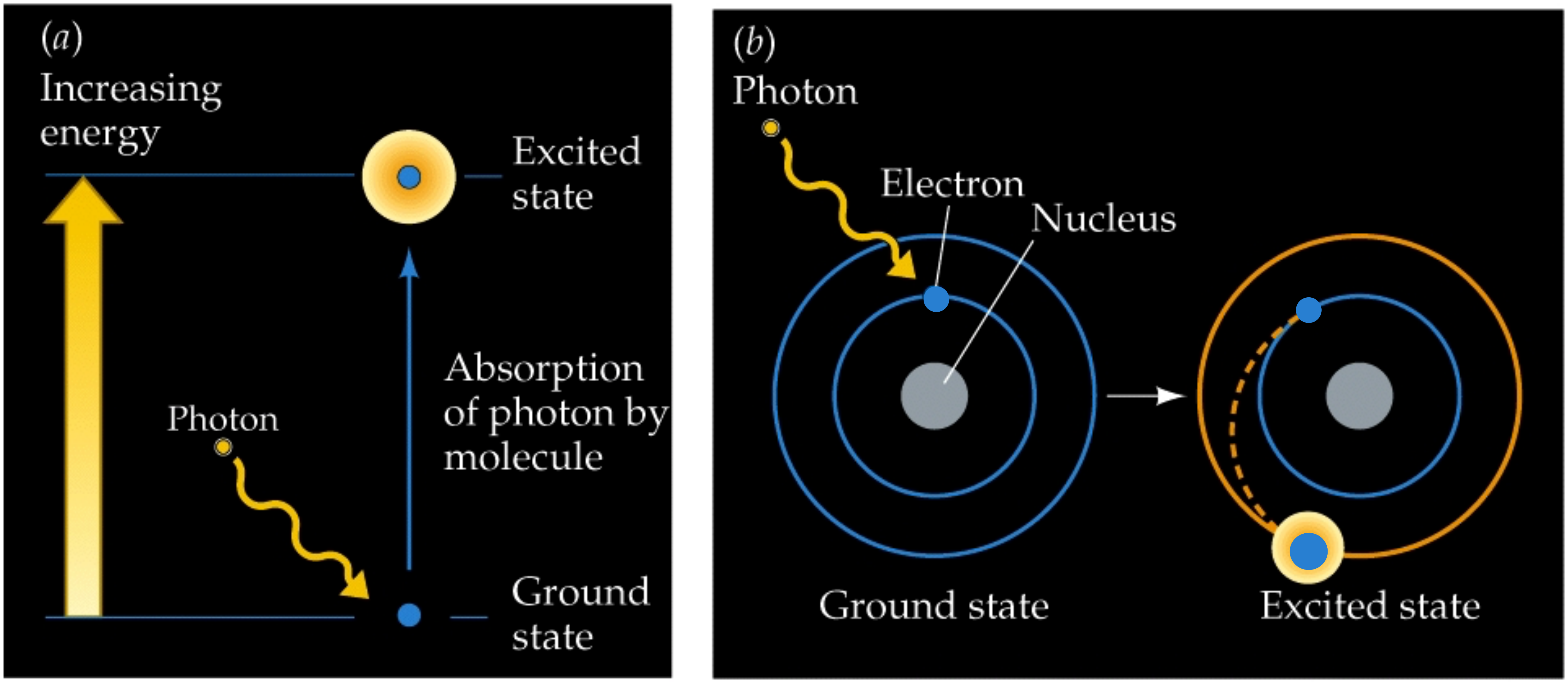

A Plant Cell
chloroplasts
REWIND
STOP
PLAY
SKIP
SKIP
1/10

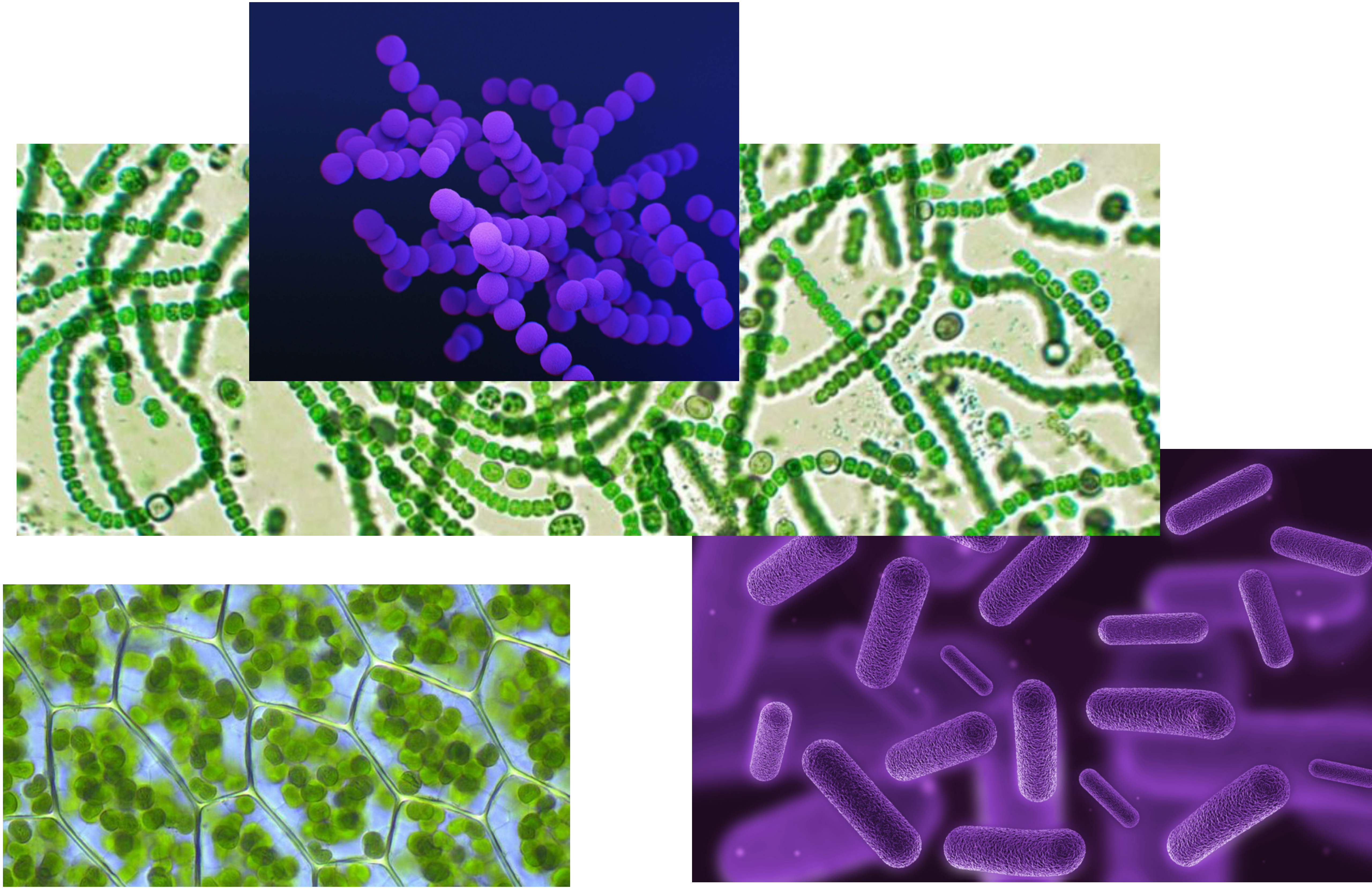
$C_6H_{12}O_6 + 6\ O_2 \longrightarrow 6\ CO_2 + 6\ H_2O$ = RESPIRATION



$C_6H_{12}O_6 + 6\ O_2 \longleftarrow 6\ CO_2 + 6\ H_2O$ + light energy = PHOTOSYNTHESIS

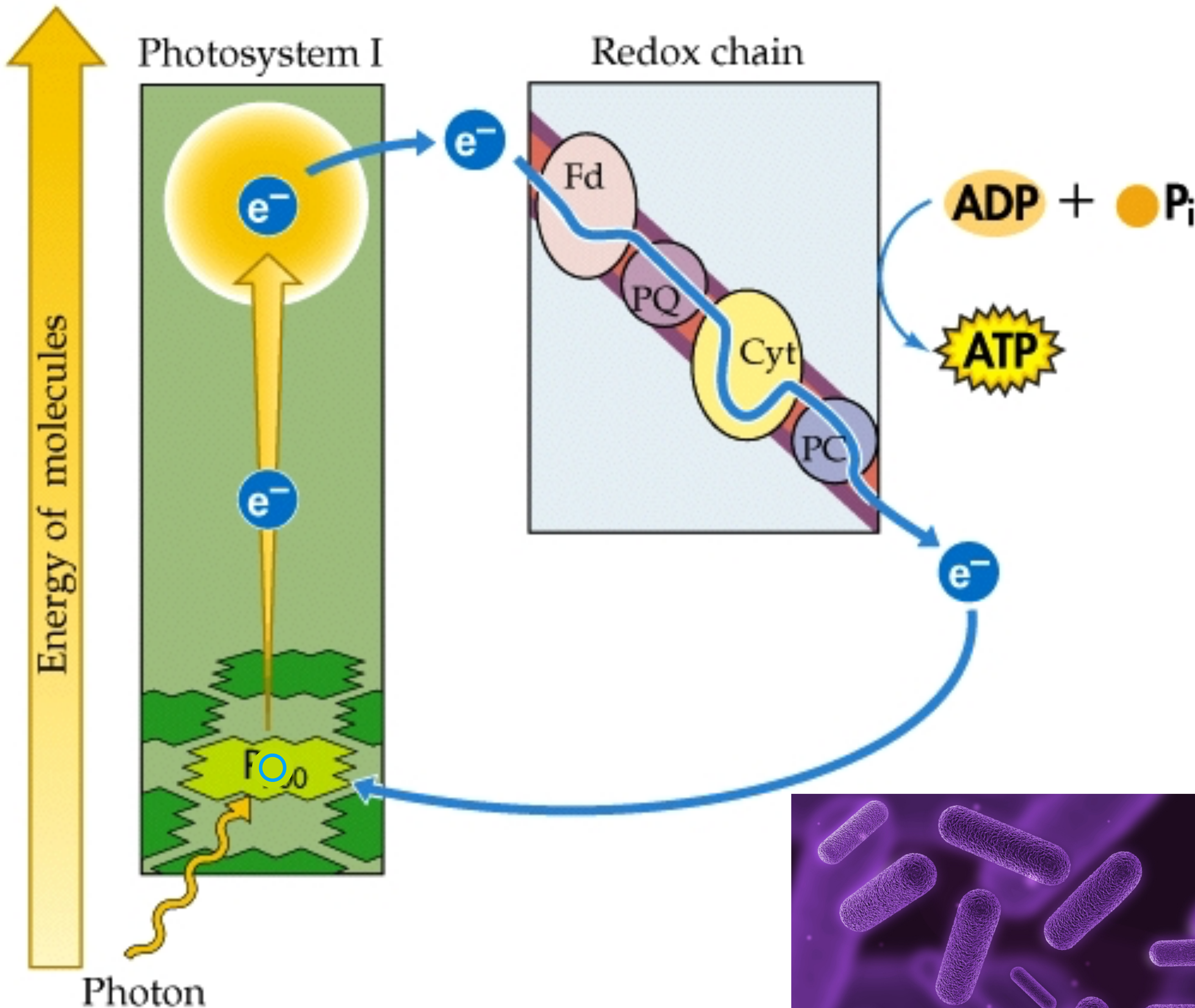

(a)
Increasing energy
Excited state
Absorption of photon by molecule
Photon
Ground state
(b)
Photon
Electron
Nucleus
Ground state
Excited state


(a)
Increasing energy
Excited state
Absorption of photon by molecule
Photon
Ground state
(b)
Photon
Electron
Nucleus
Ground state
Excited state



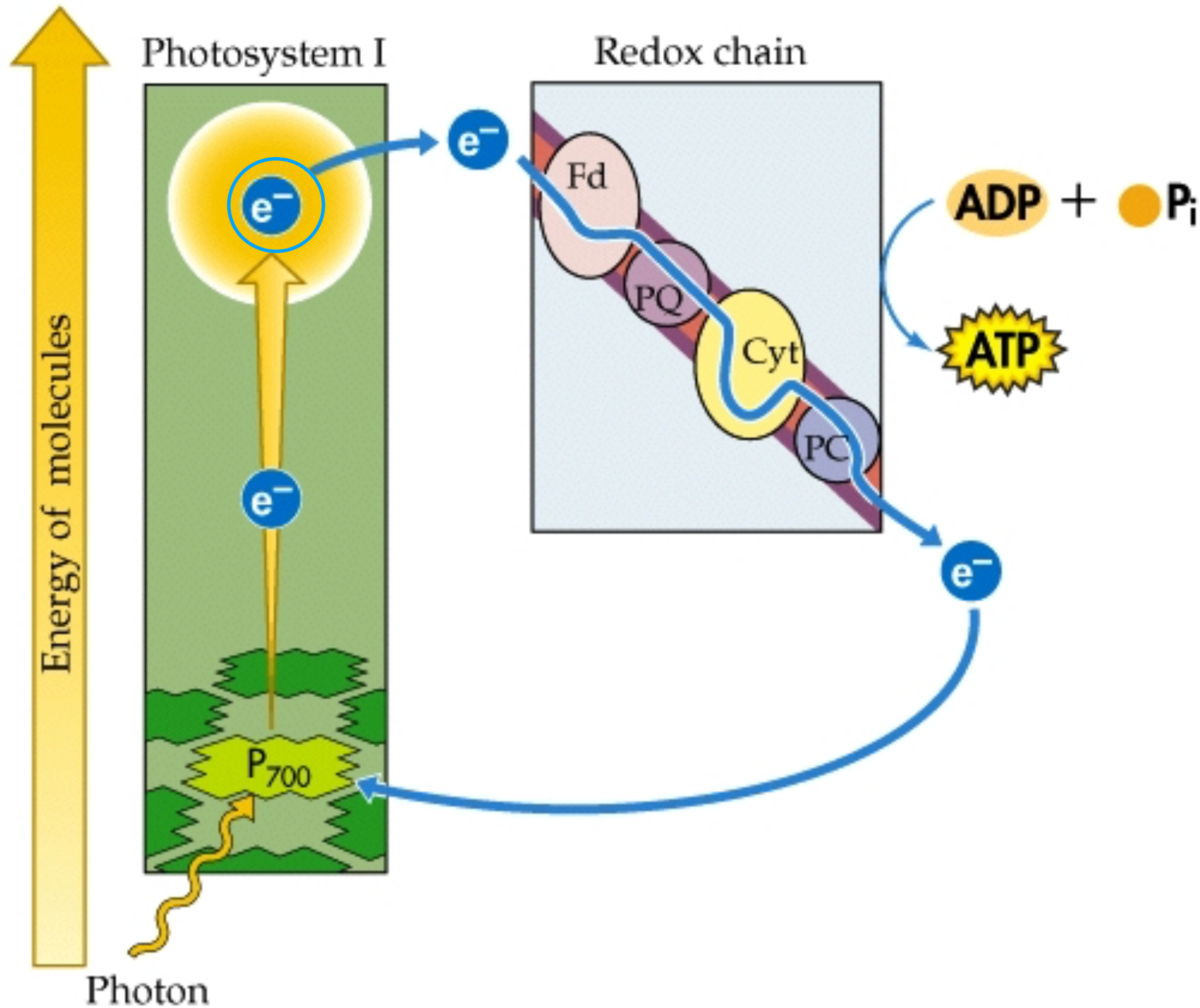
Cyanobacteria

purple bacteria

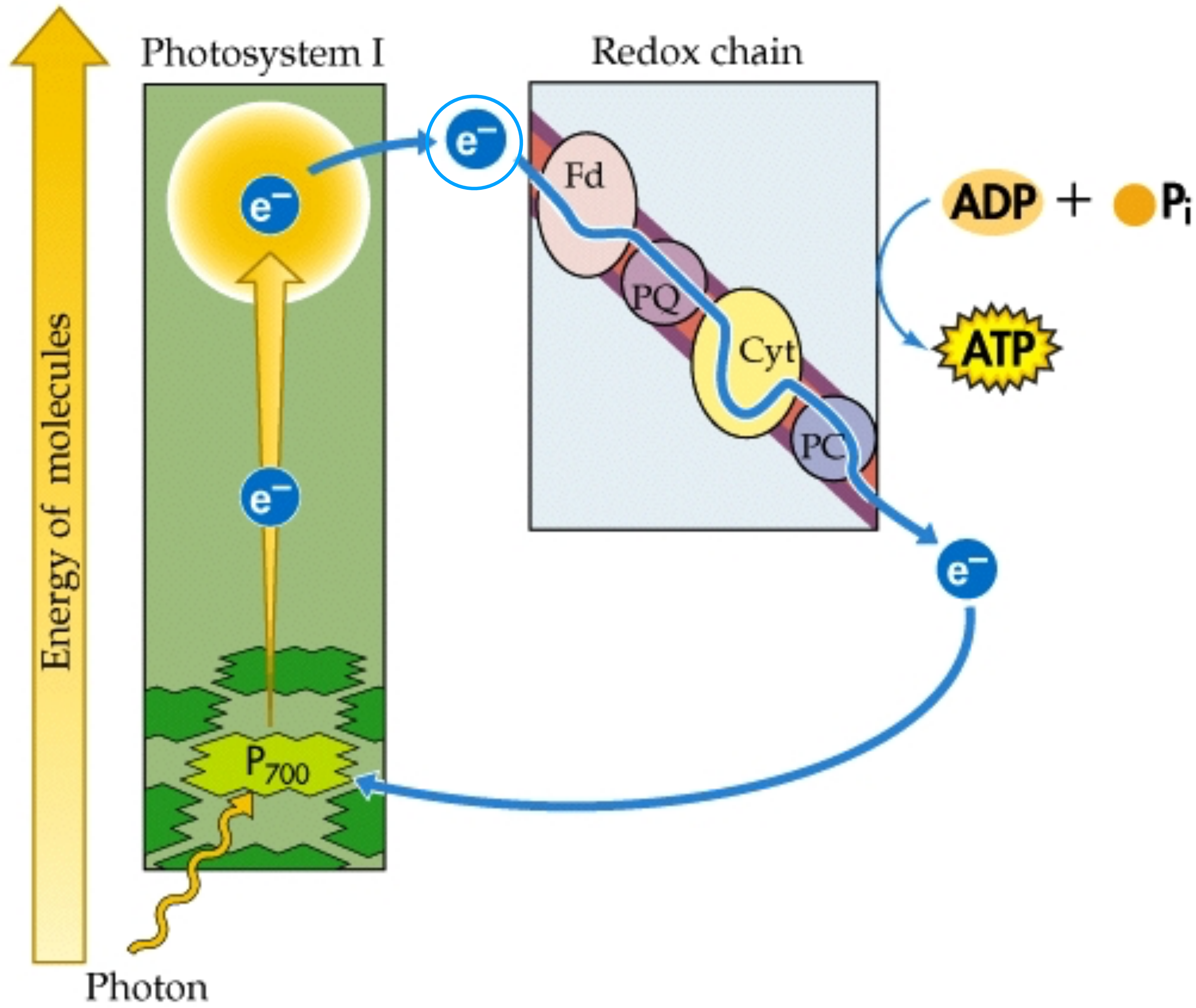


Anoxygenic photosynthesis…. “Cyclic”

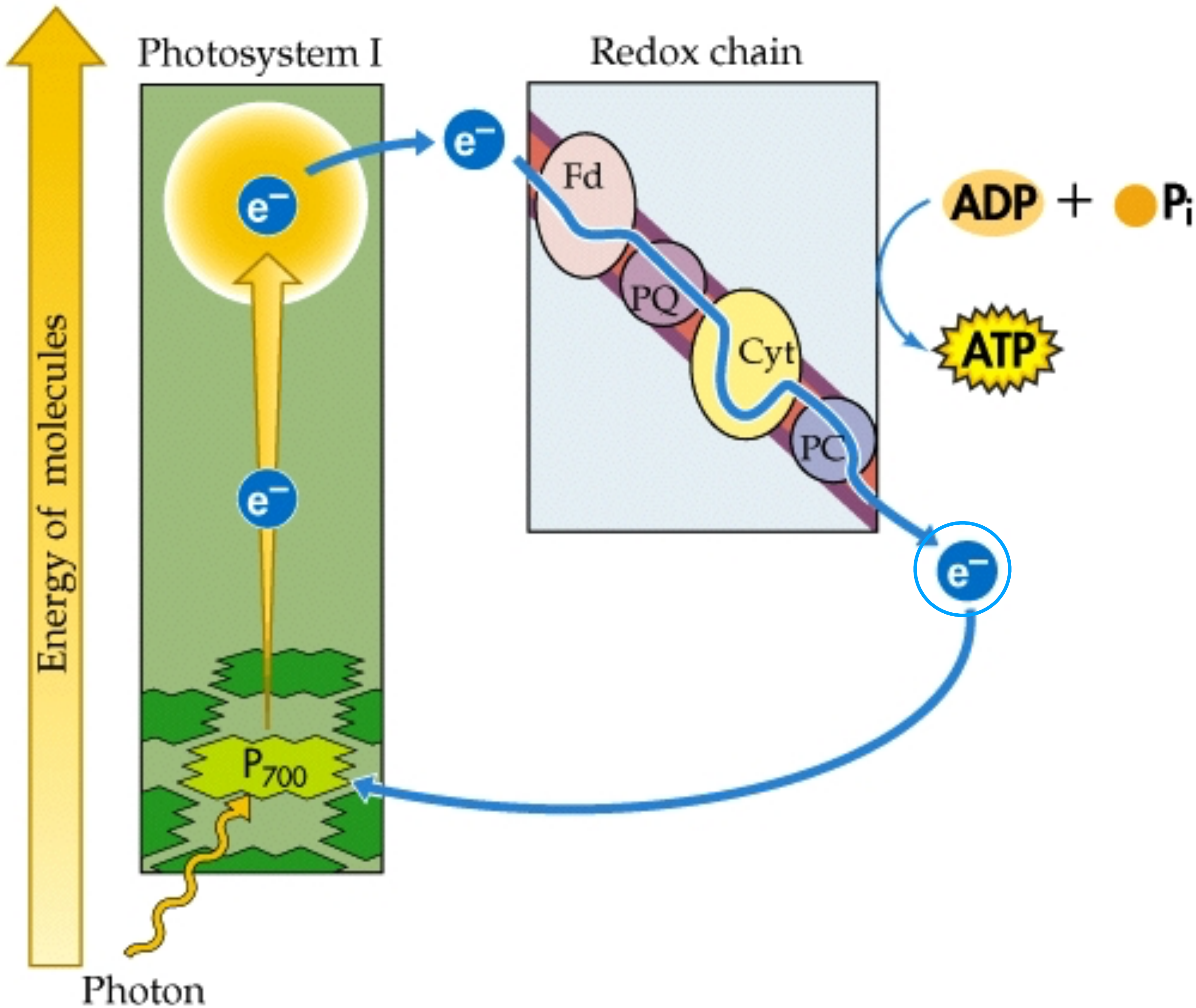
purple bacteria



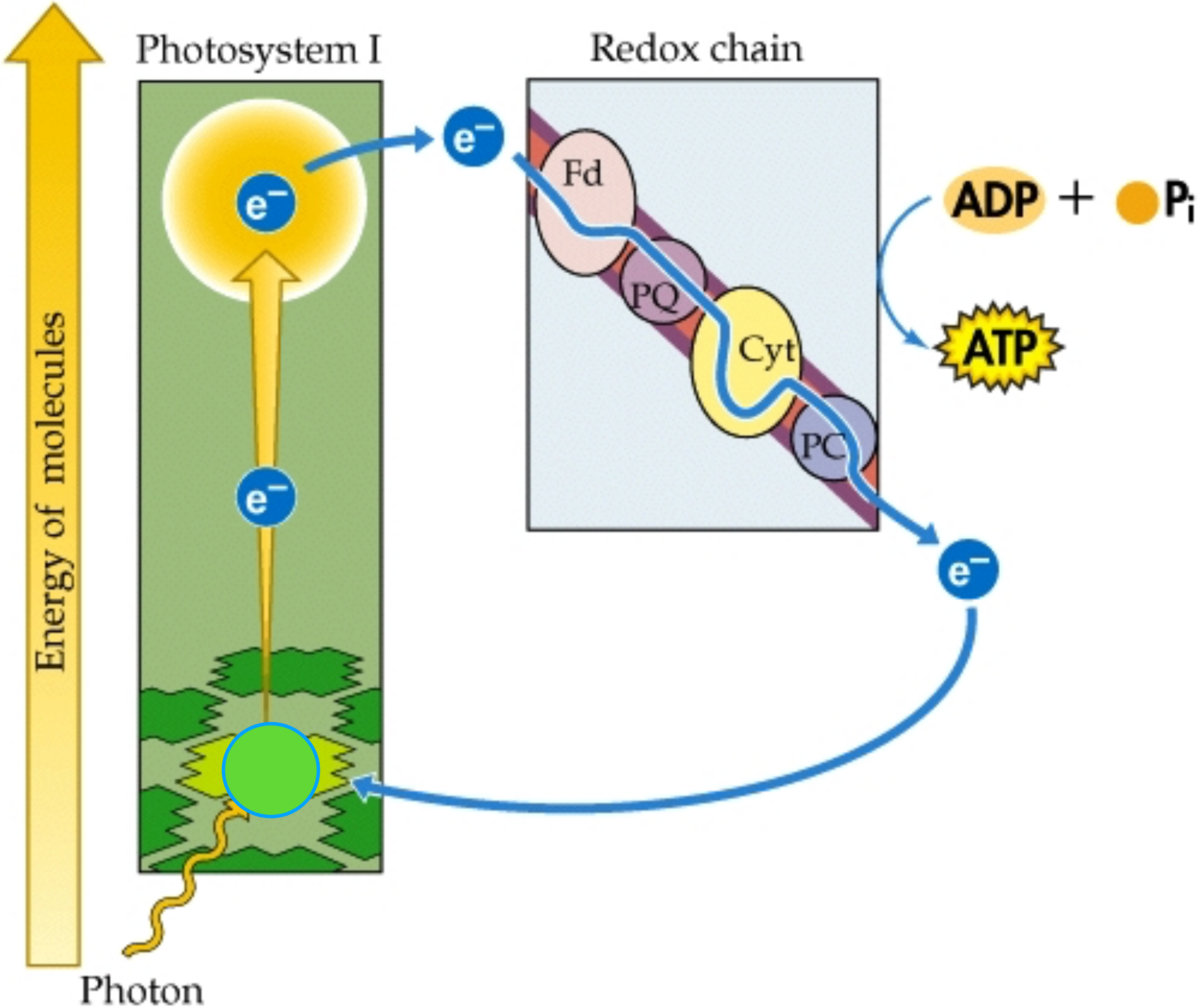
Photosystem I
Redox chain
Energy of molecules
e⁻
Fd
PQ
Cyt
PC
ADP + Pi
ATP
P700
Photon

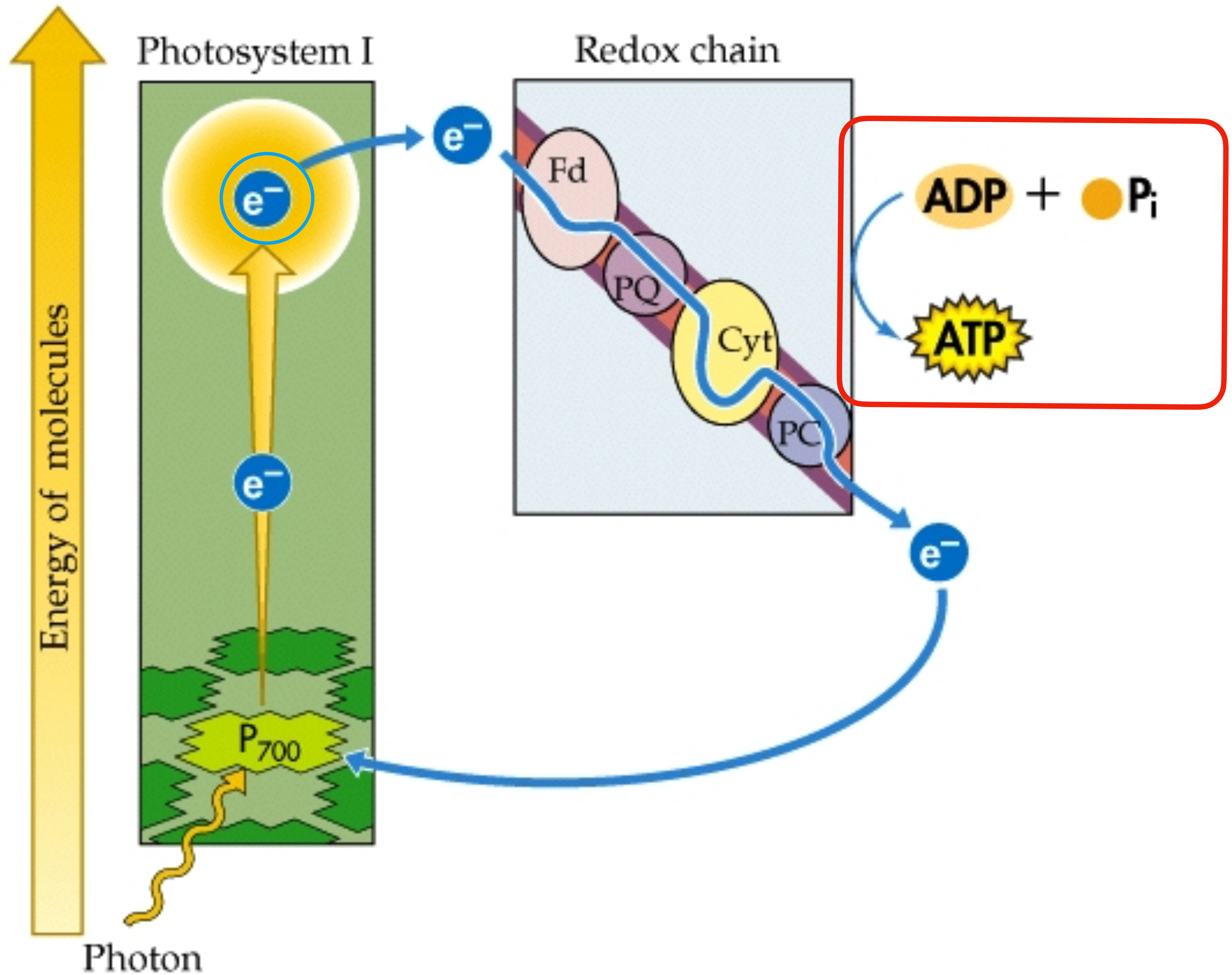


Photosystem I
Redox chain
Energy of molecules
e⁻
Fd
PQ
Cyt
PC
ADP + Pi
ATP
P700
Photon



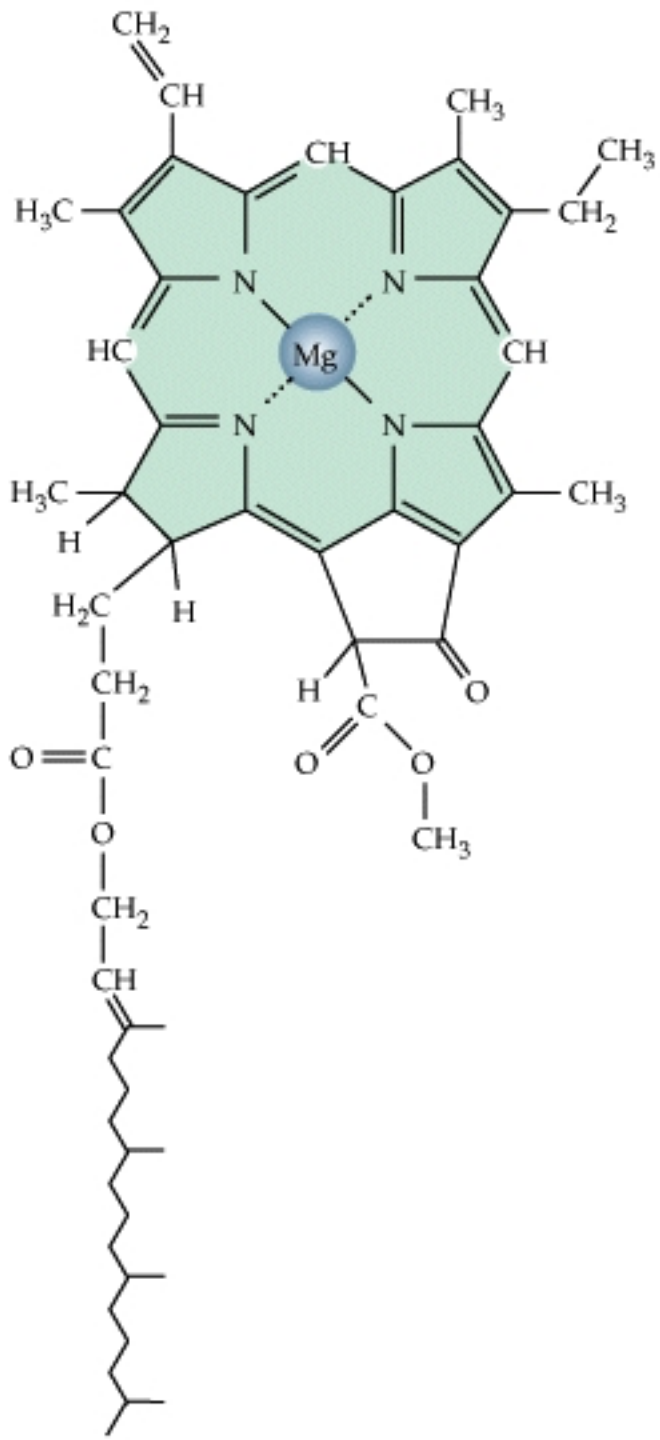
Photosystem I
Redox chain
Energy of molecules
e⁻
Fd
PQ
Cyt
PC
ADP + Pi
ATP
P700
Photon

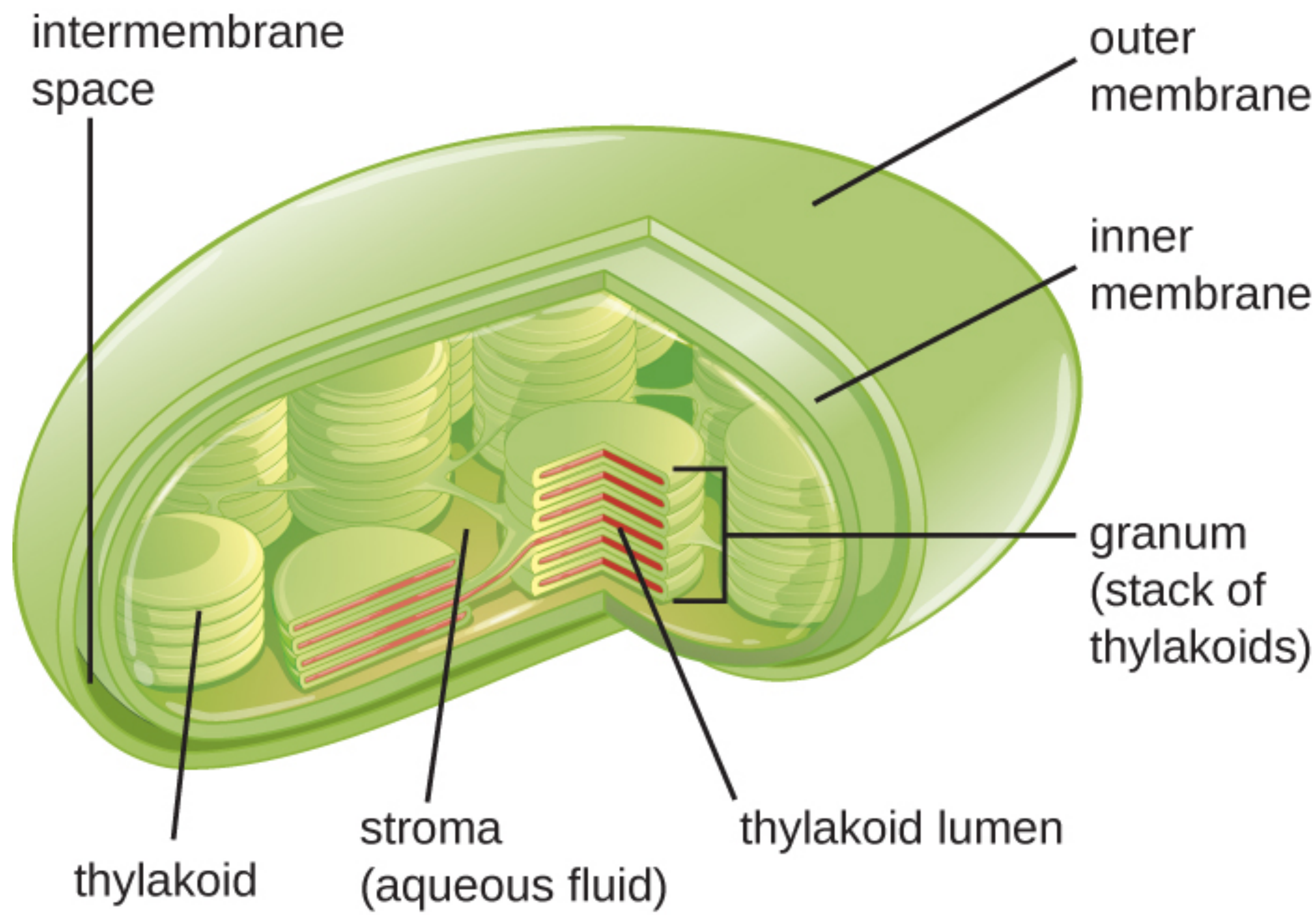

Photosystem I
Redox chain
Energy of molecules
e⁻
Fd
PQ
Cyt
PC
ADP + Pi
ATP
Photon



Photosystem I
Redox chain
Energy of molecules
e⁻
Fd
PQ
Cyt
PC
ADP + Pi
ATP
P700
Photon

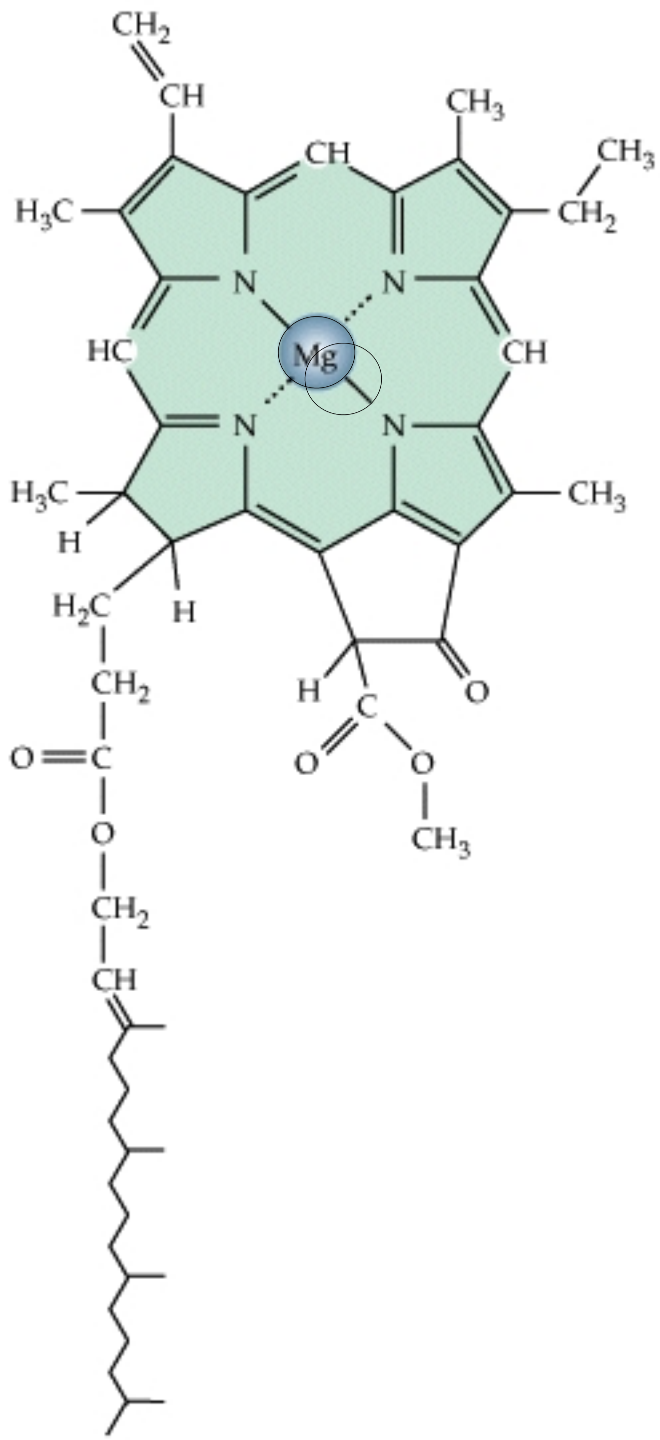
Chlorophyll *a*

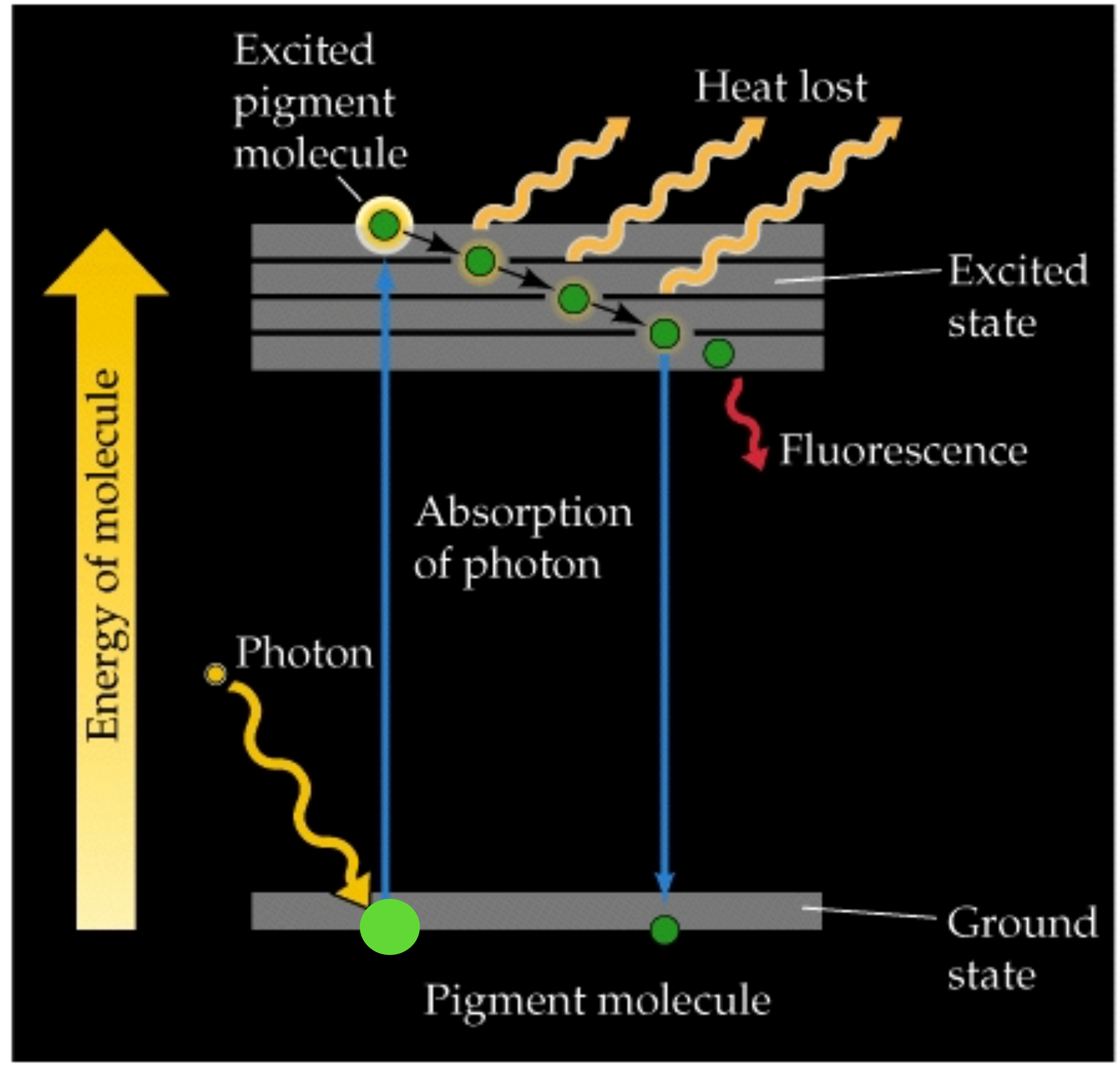




Oxygenic photosynthesis… Plants and Cyanobacteria

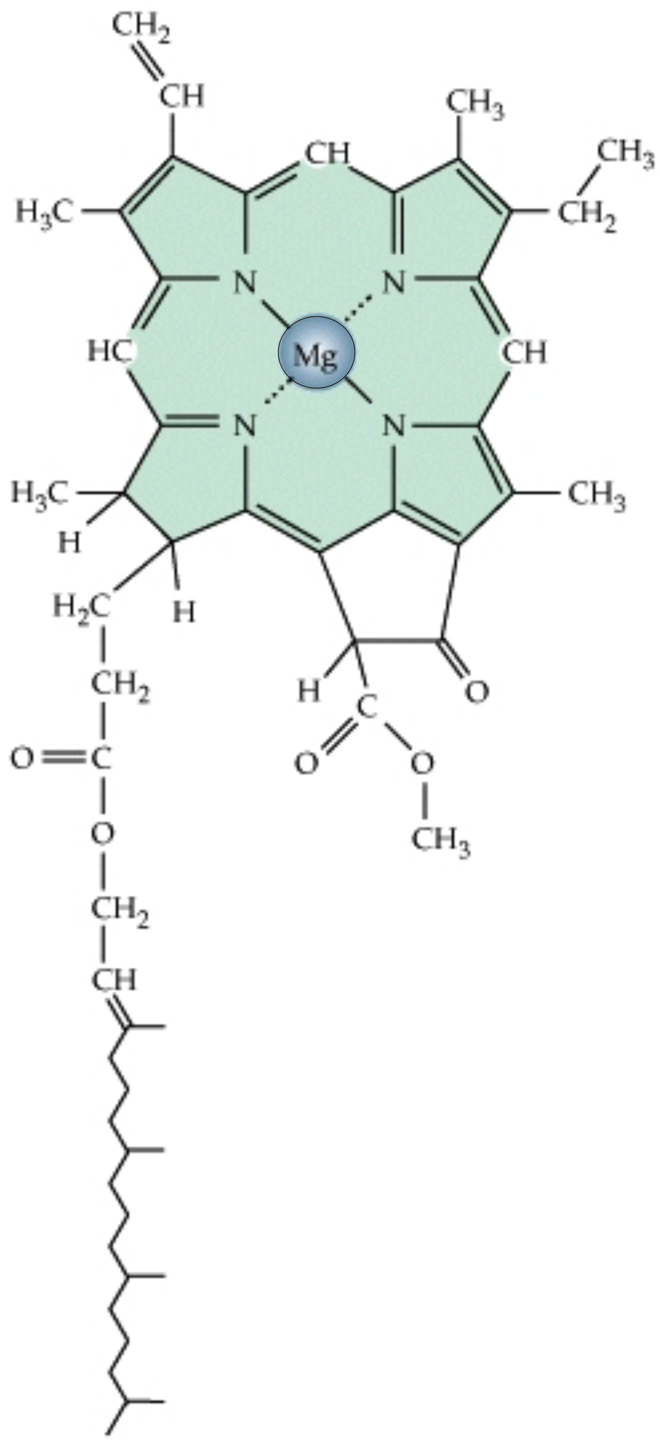
Chlorophyll *a*

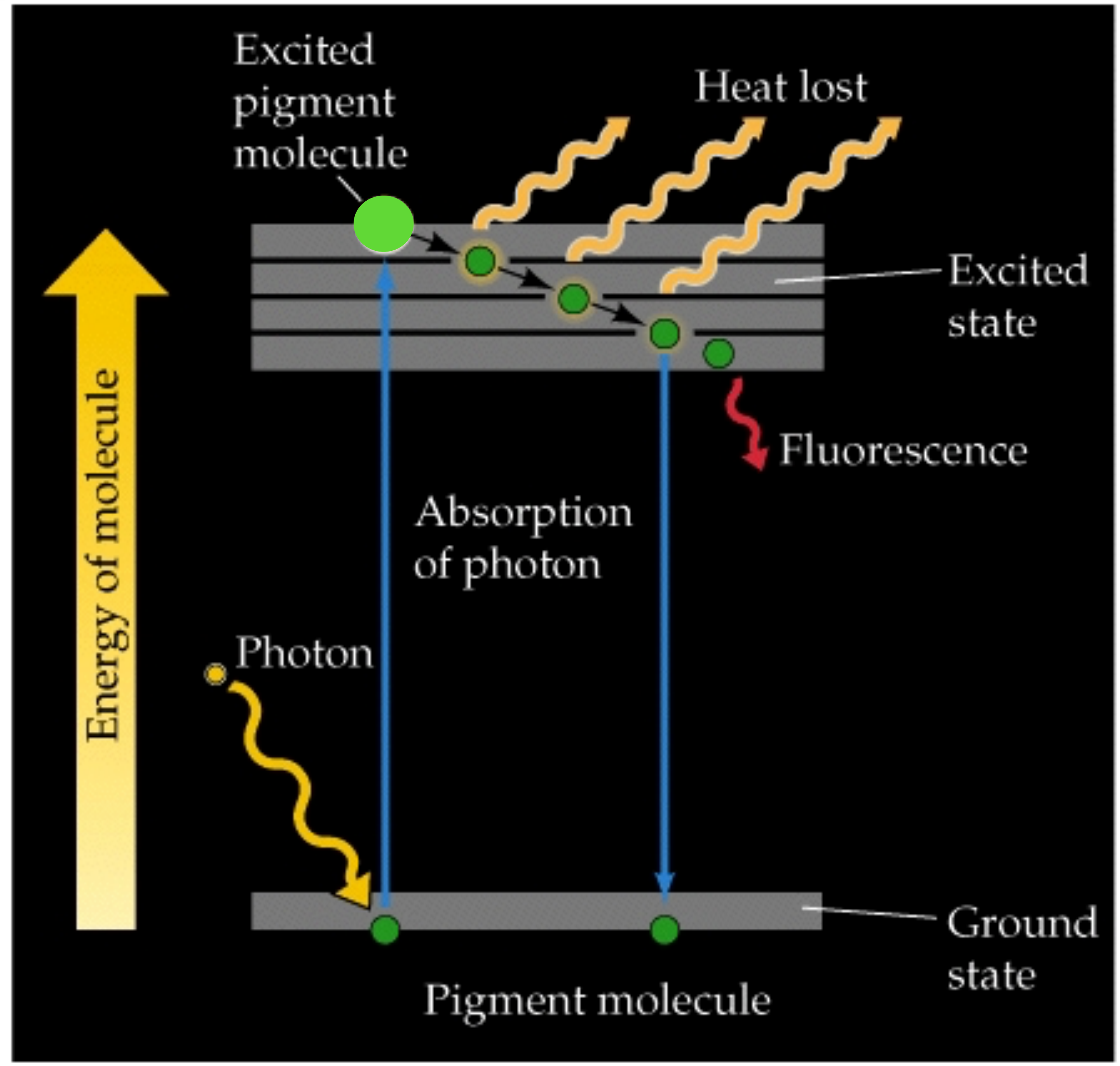




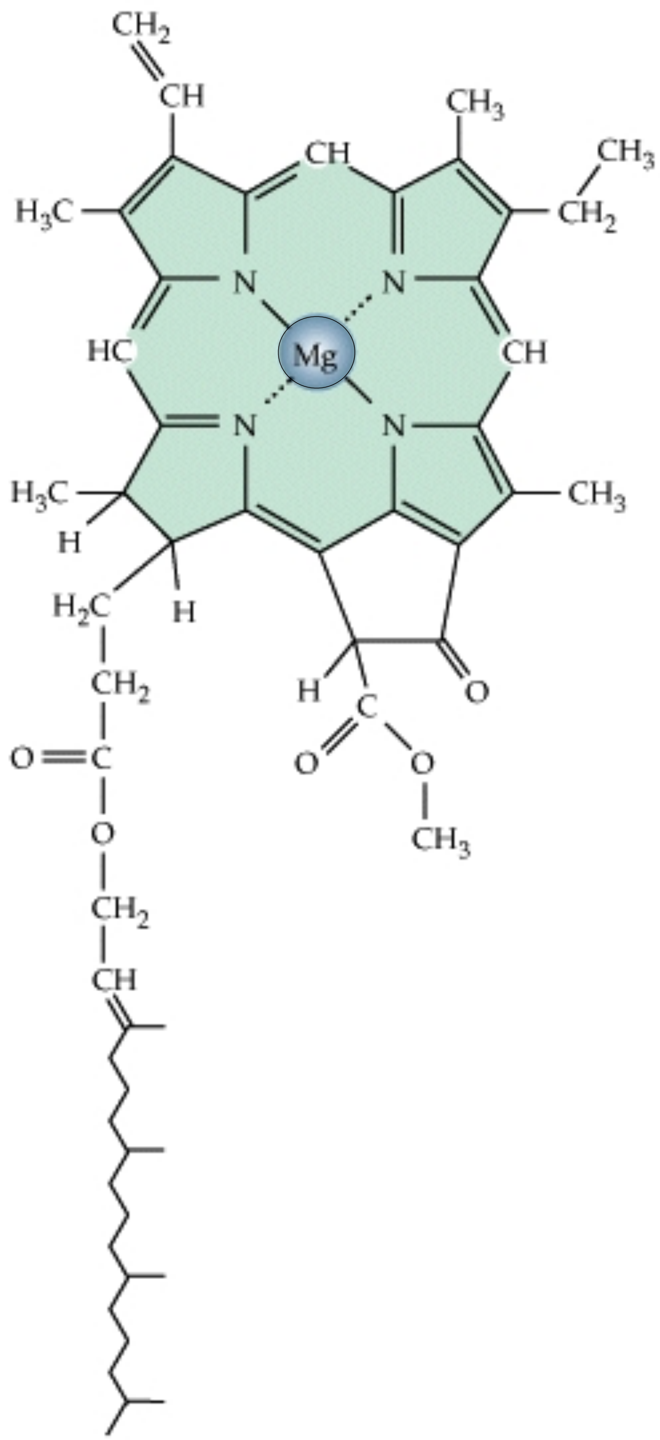
Oxygenic photosynthesis… Plants and Cyanobacteria

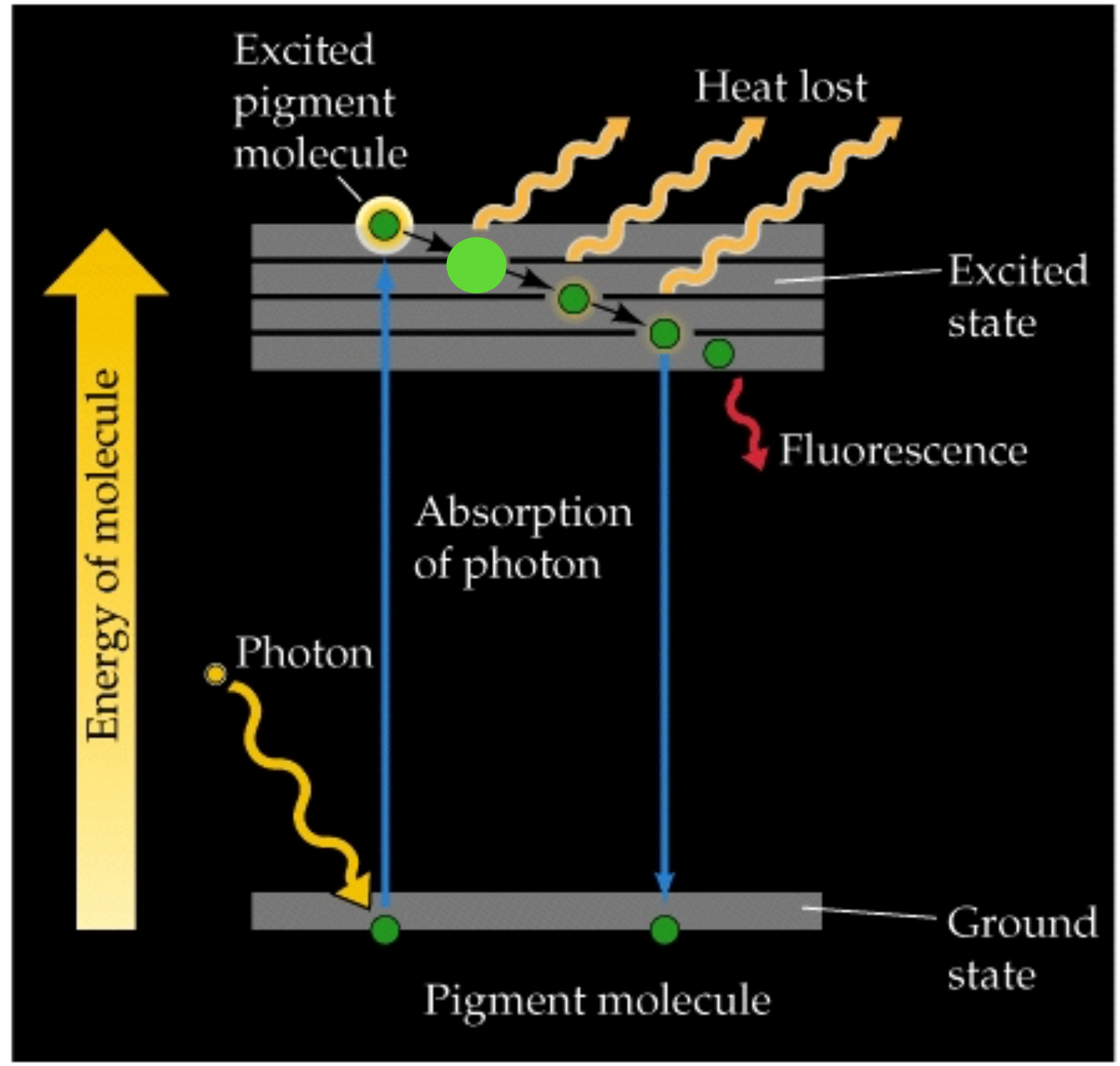
Chlorophyll *a*



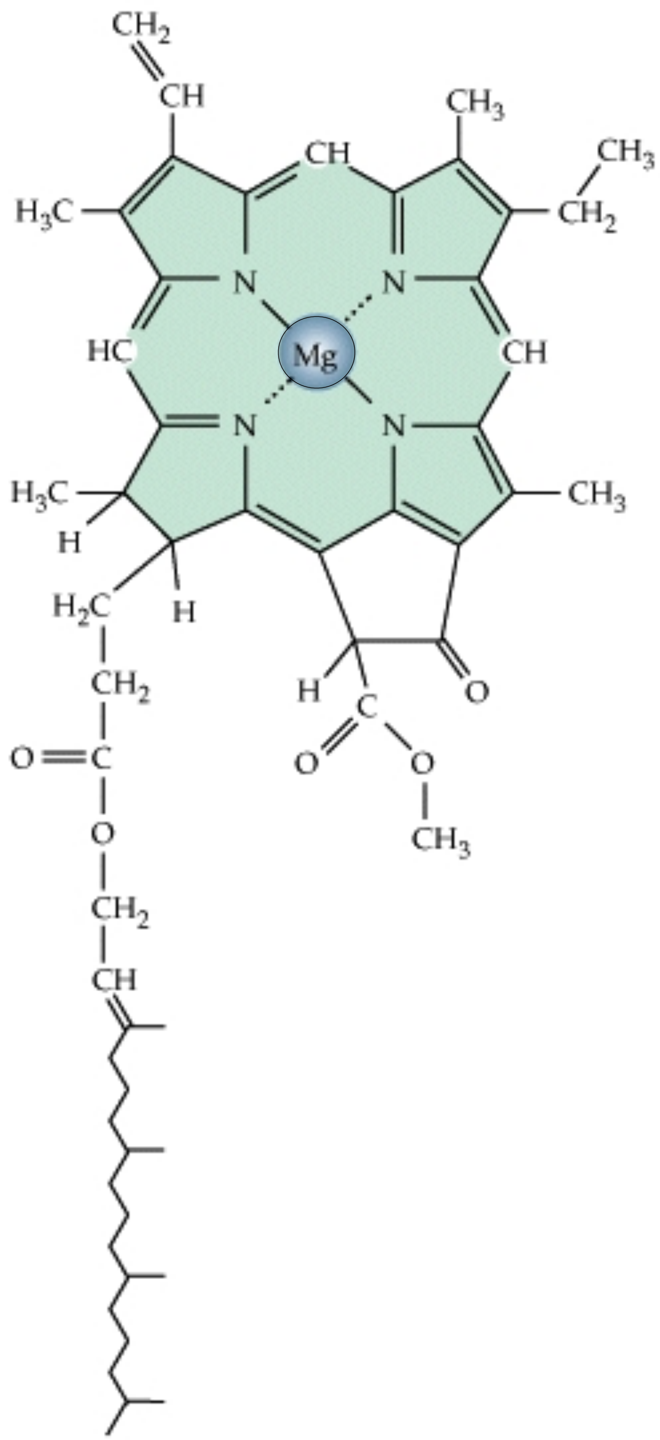


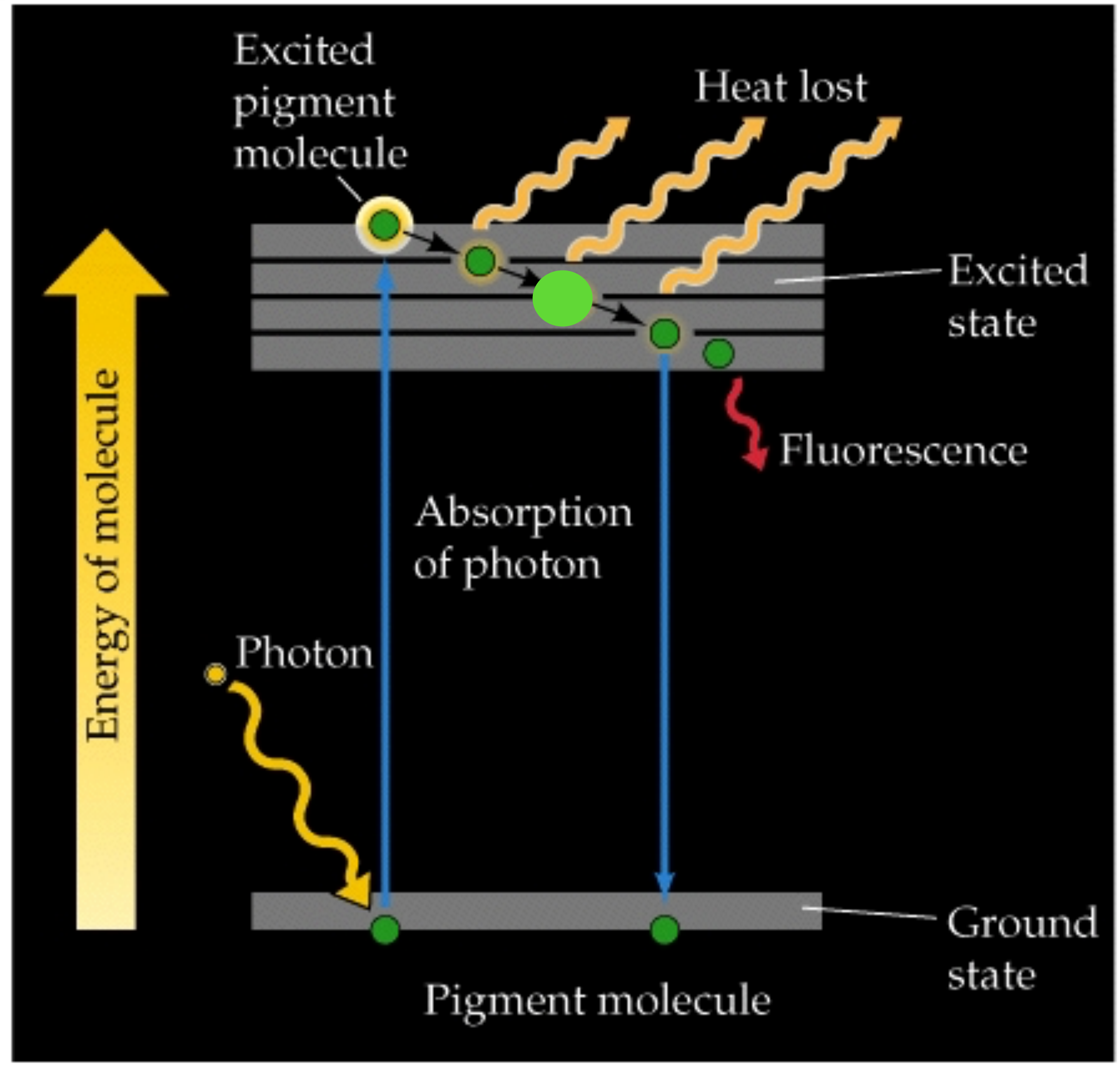
Chlorophyll *a*



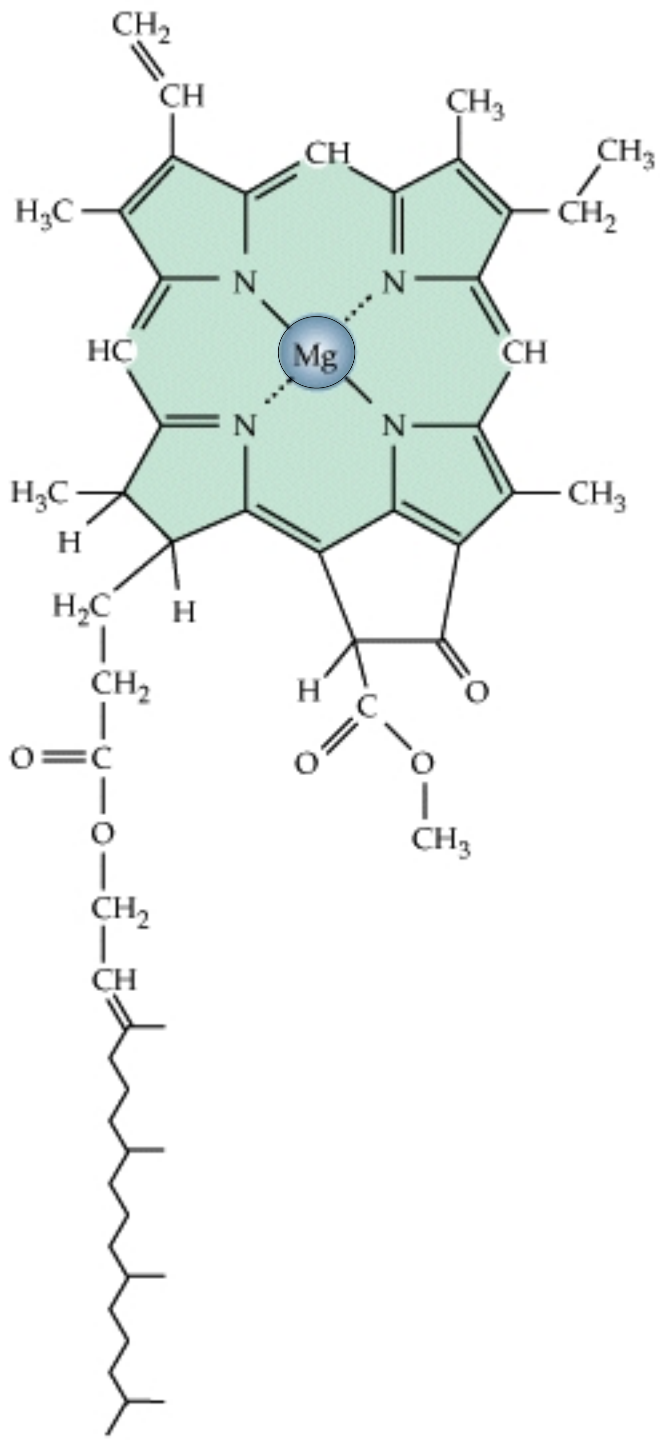


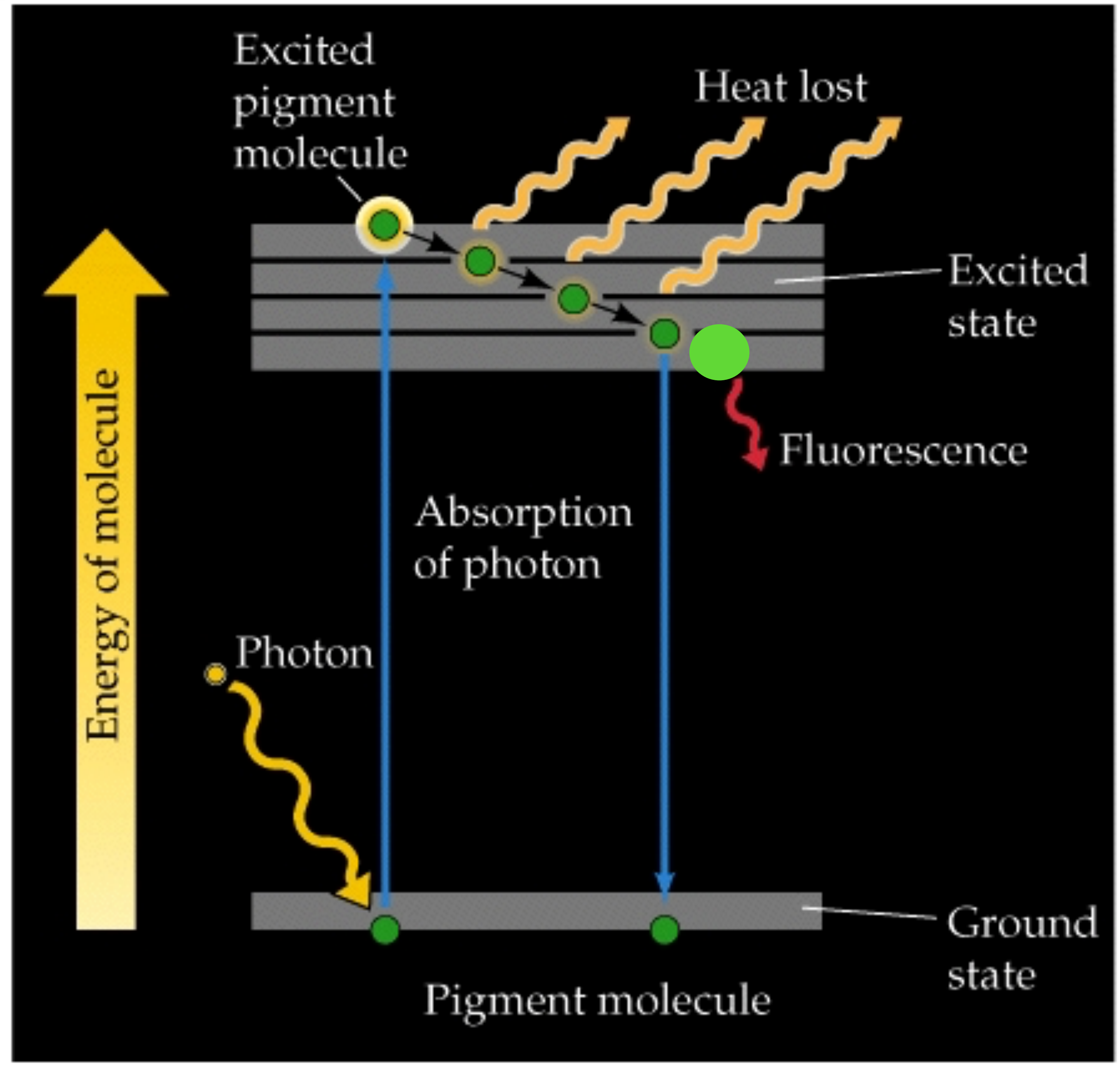
Chlorophyll *a*



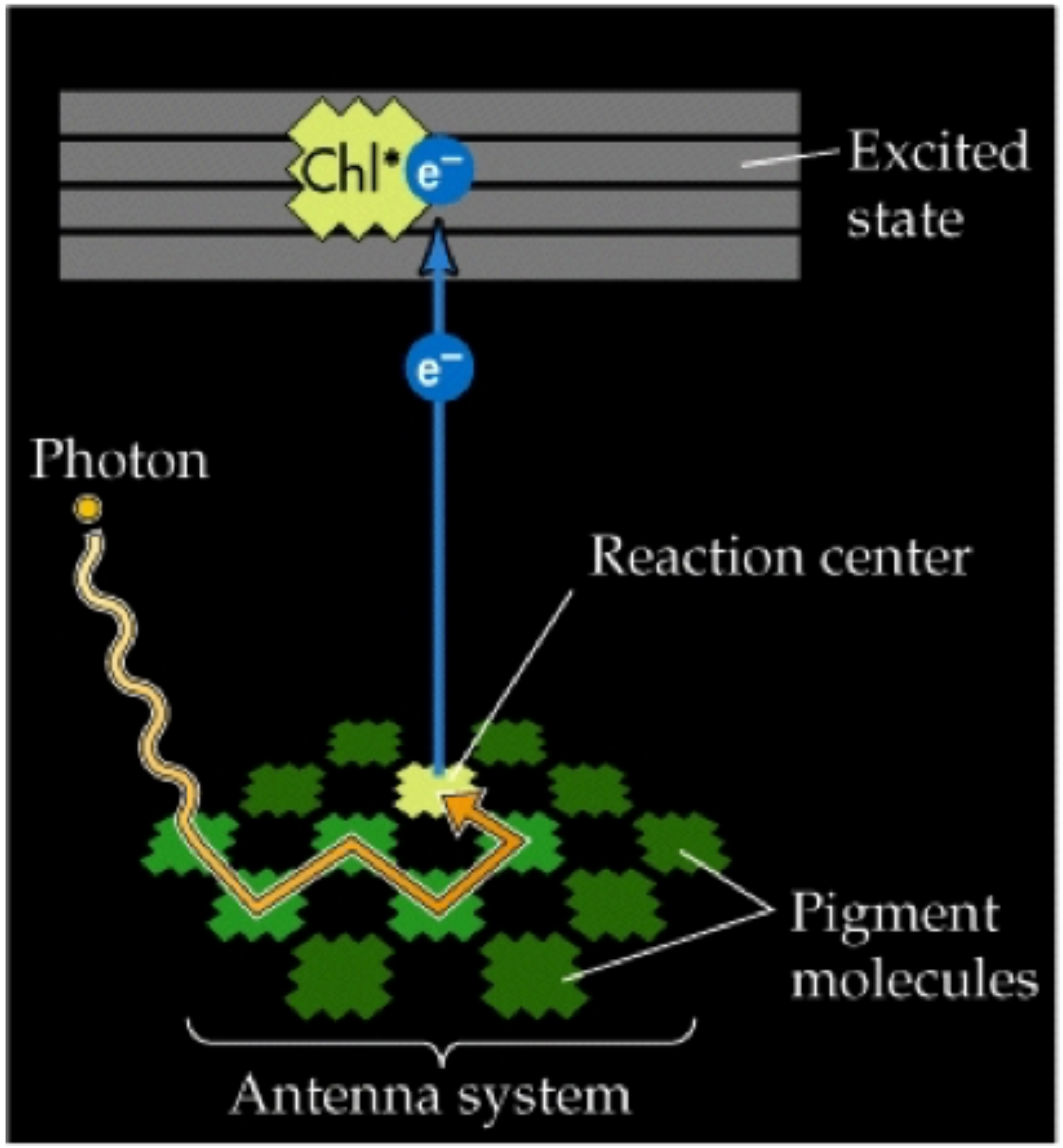


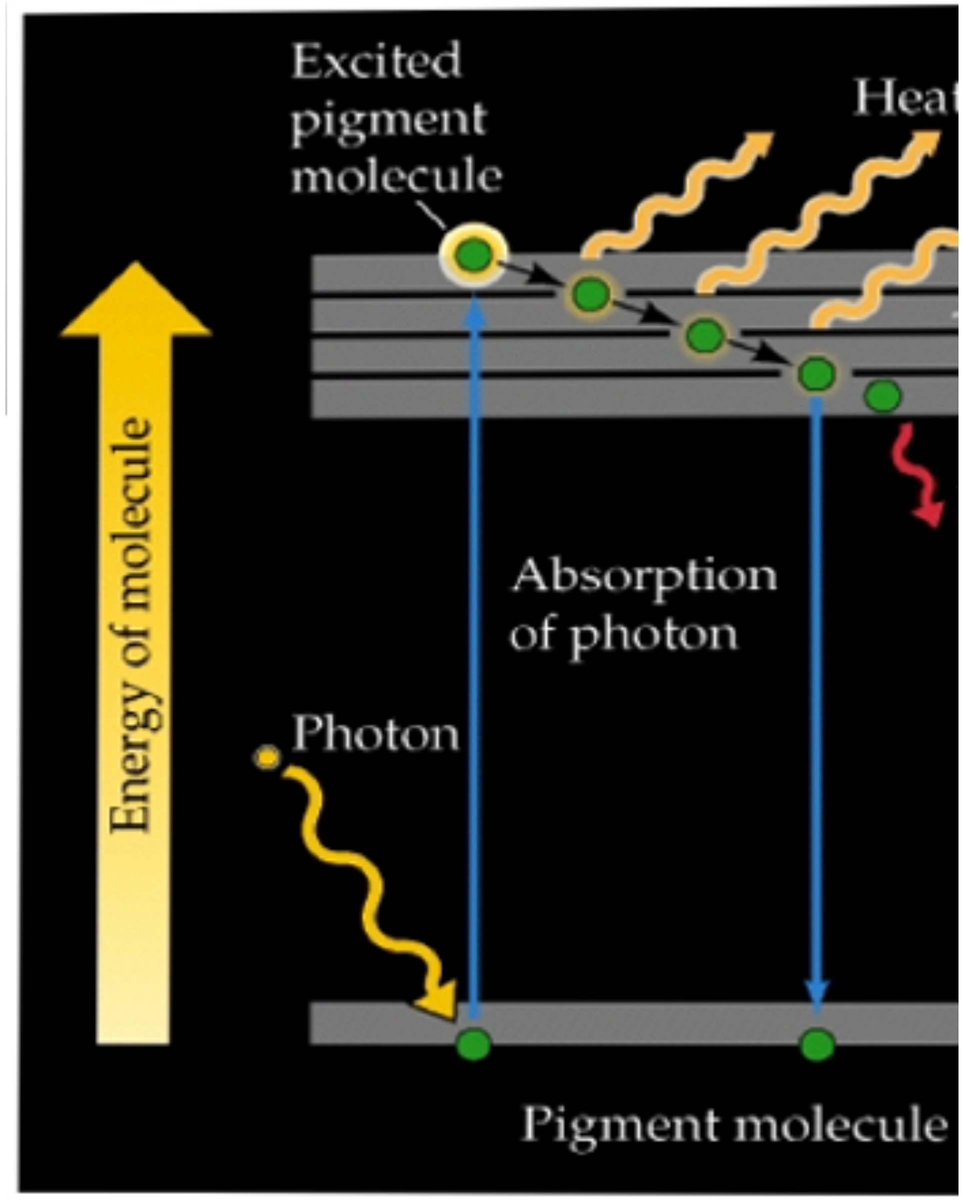
Chlorophyll *a*

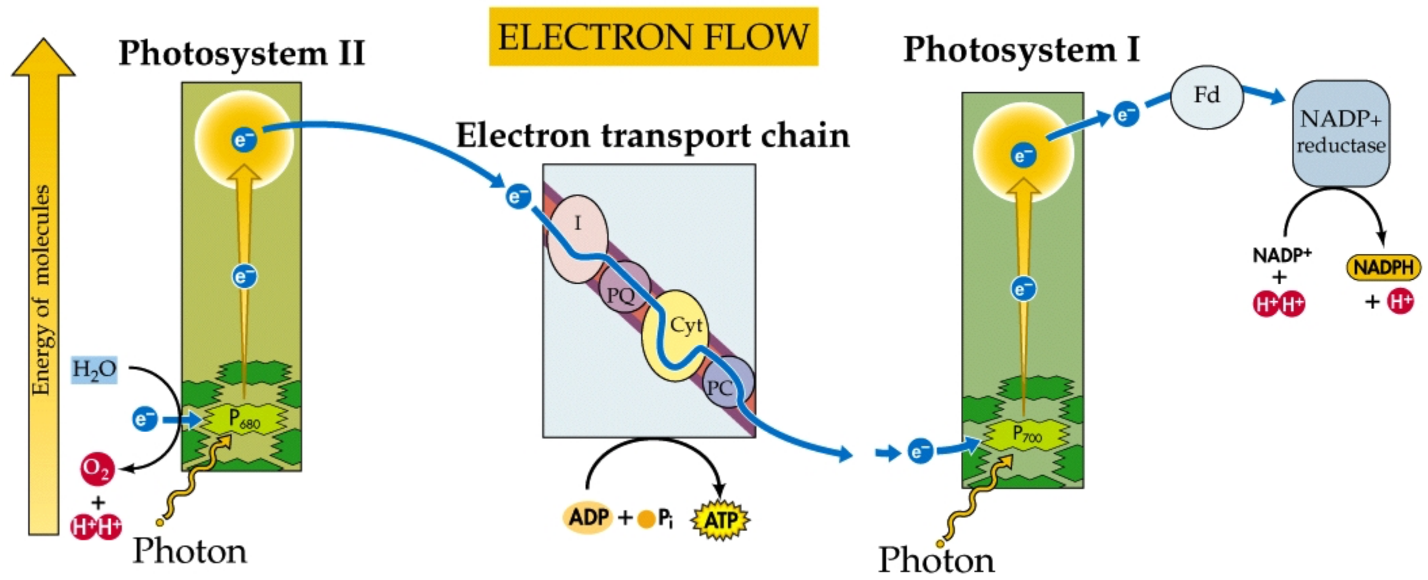




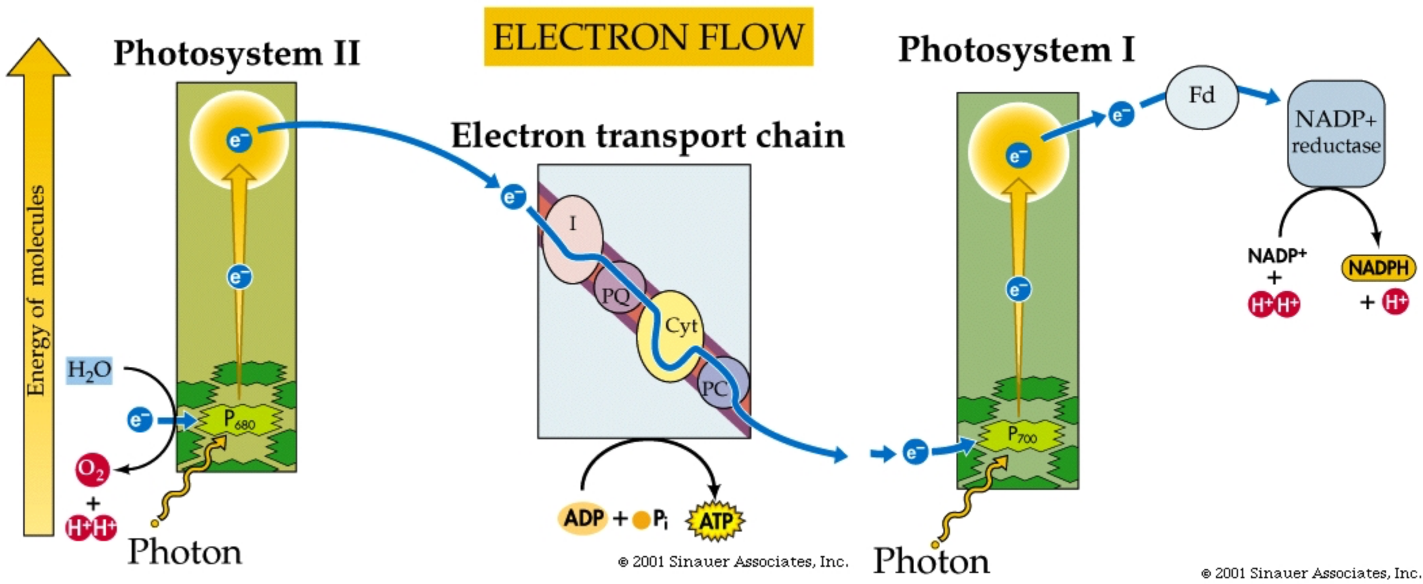
(*a*) Energy transfer

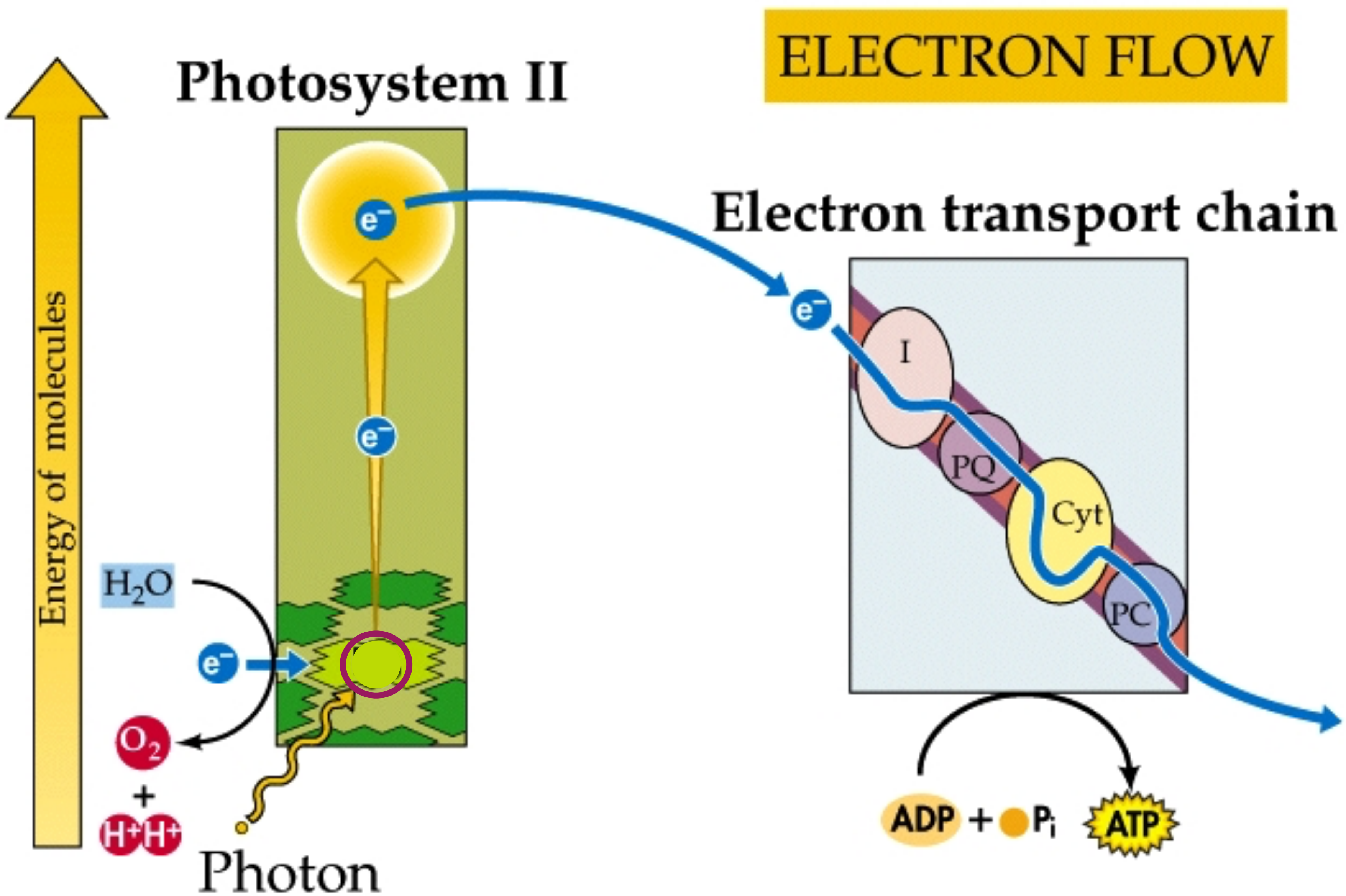


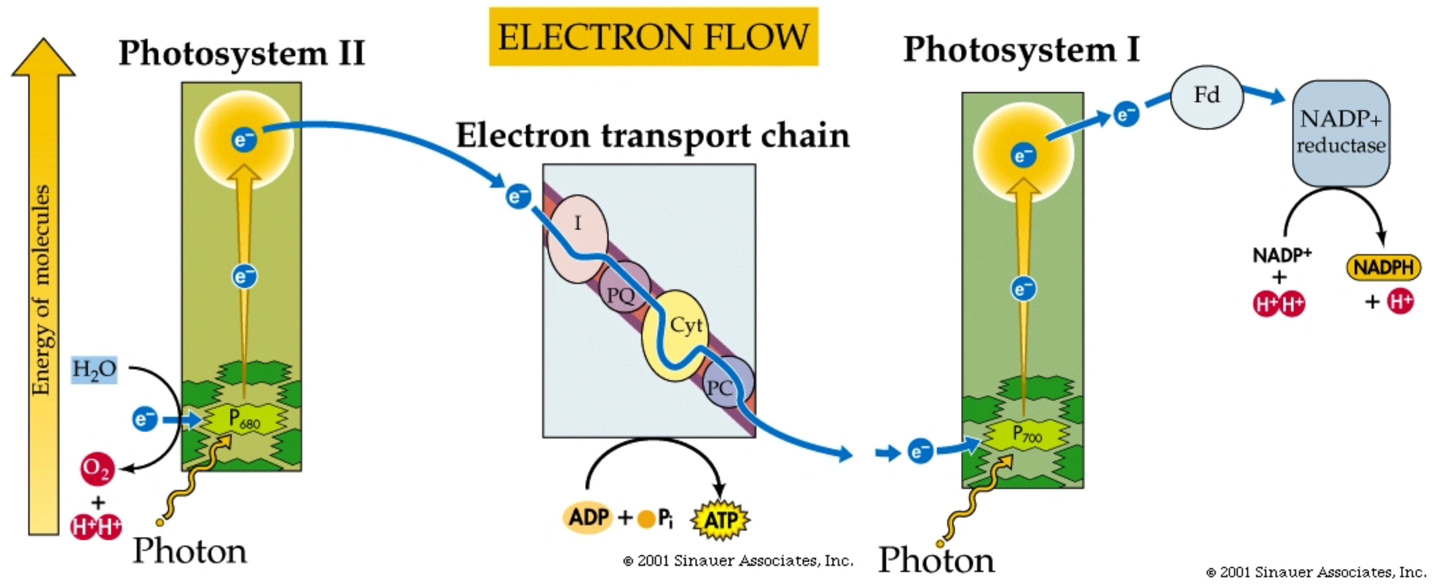


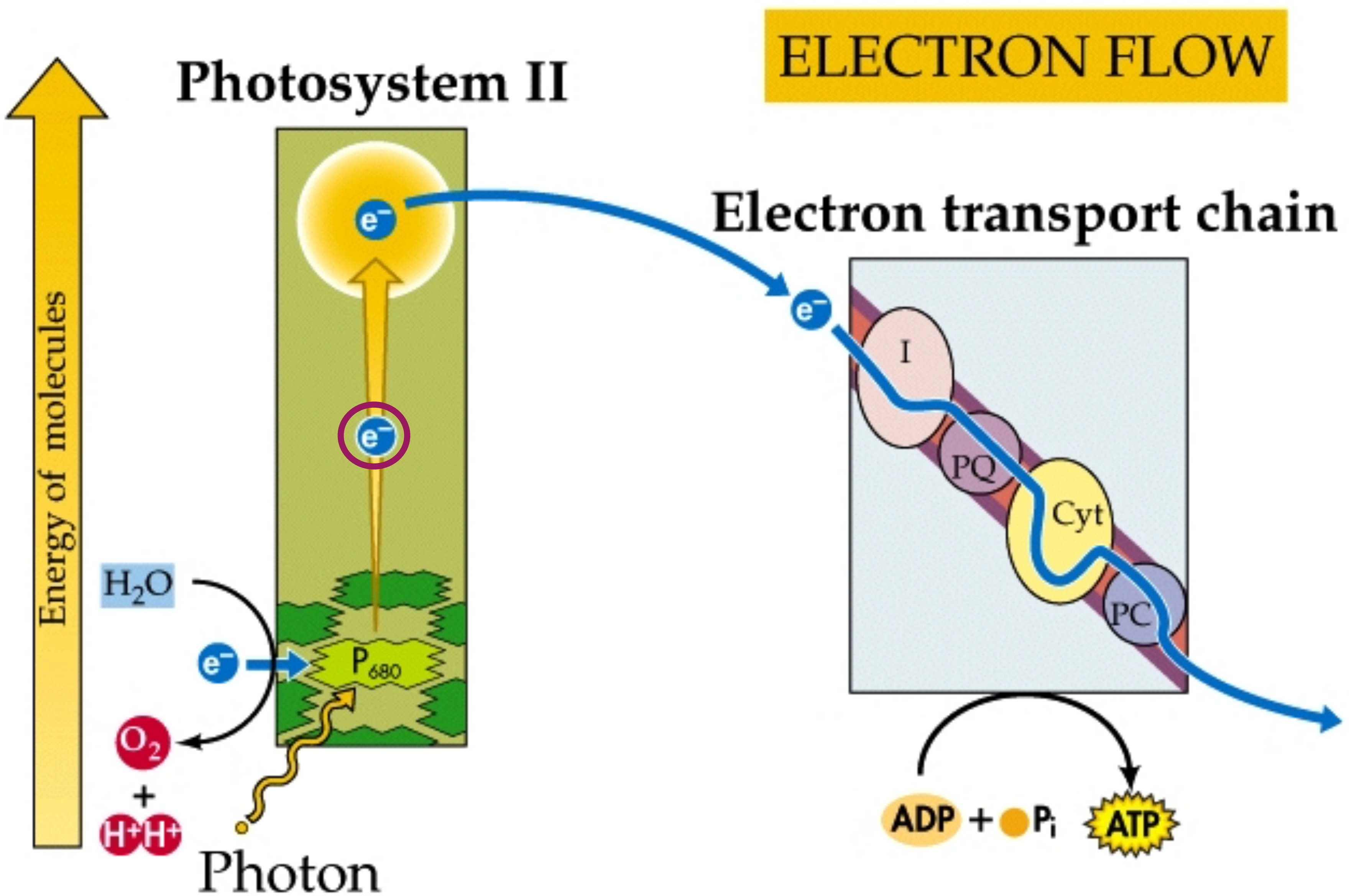


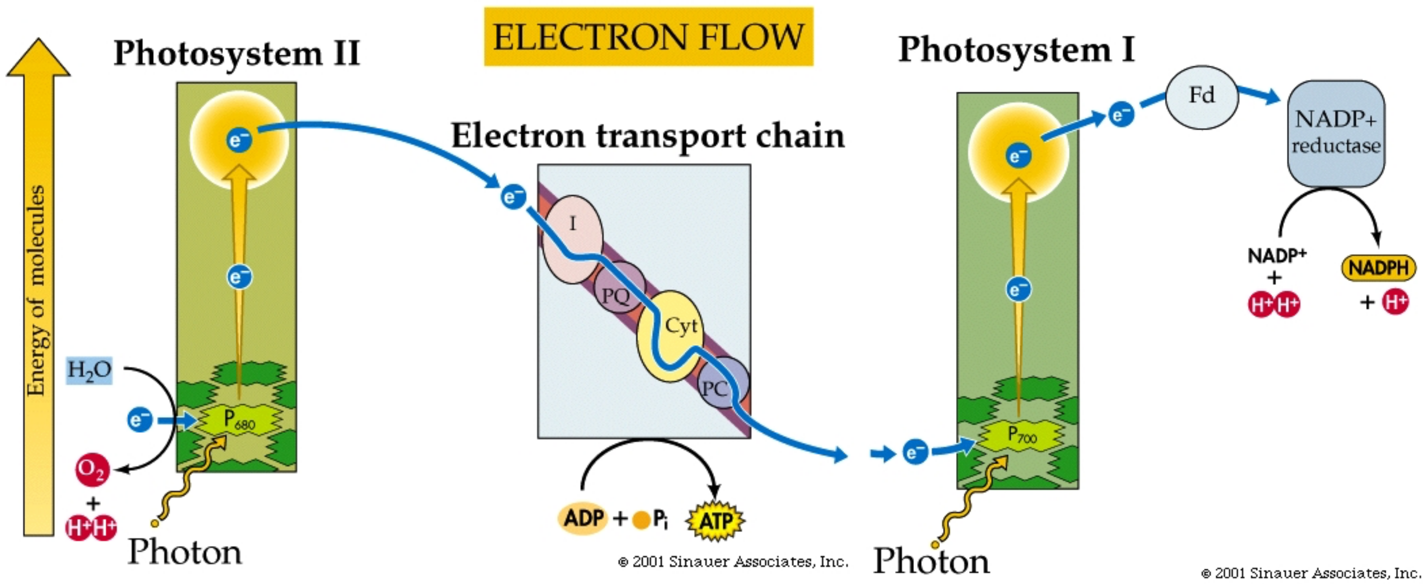
ELECTRON FLOW
Photosystem II
Electron transport chain
Photosystem I
Energy of molecules
H_2O
e⁻
O_2
+
H⁺ H⁺
P_{680}
Photon
I
PQ
Cyt
PC
ADP + Pi
ATP
P_{700}
Photon
Fd
NADP+
reductase
NADP⁺
+
H⁺ H⁺
NADPH
+ H⁺


ELECTRON FLOW
Photosystem II
Photosystem I
Electron transport chain
Energy of molecules
H2O
e−
O2
+
H+H+
P680
Photon
I
PQ
Cyt
PC
ADP + Pi
ATP
© 2001 Sinauer Associates, Inc.
P700
Photon
Fd
NADP+ reductase
NADP+
+
H+H+
NADPH
+ H+
© 2001 Sinauer Associates, Inc.

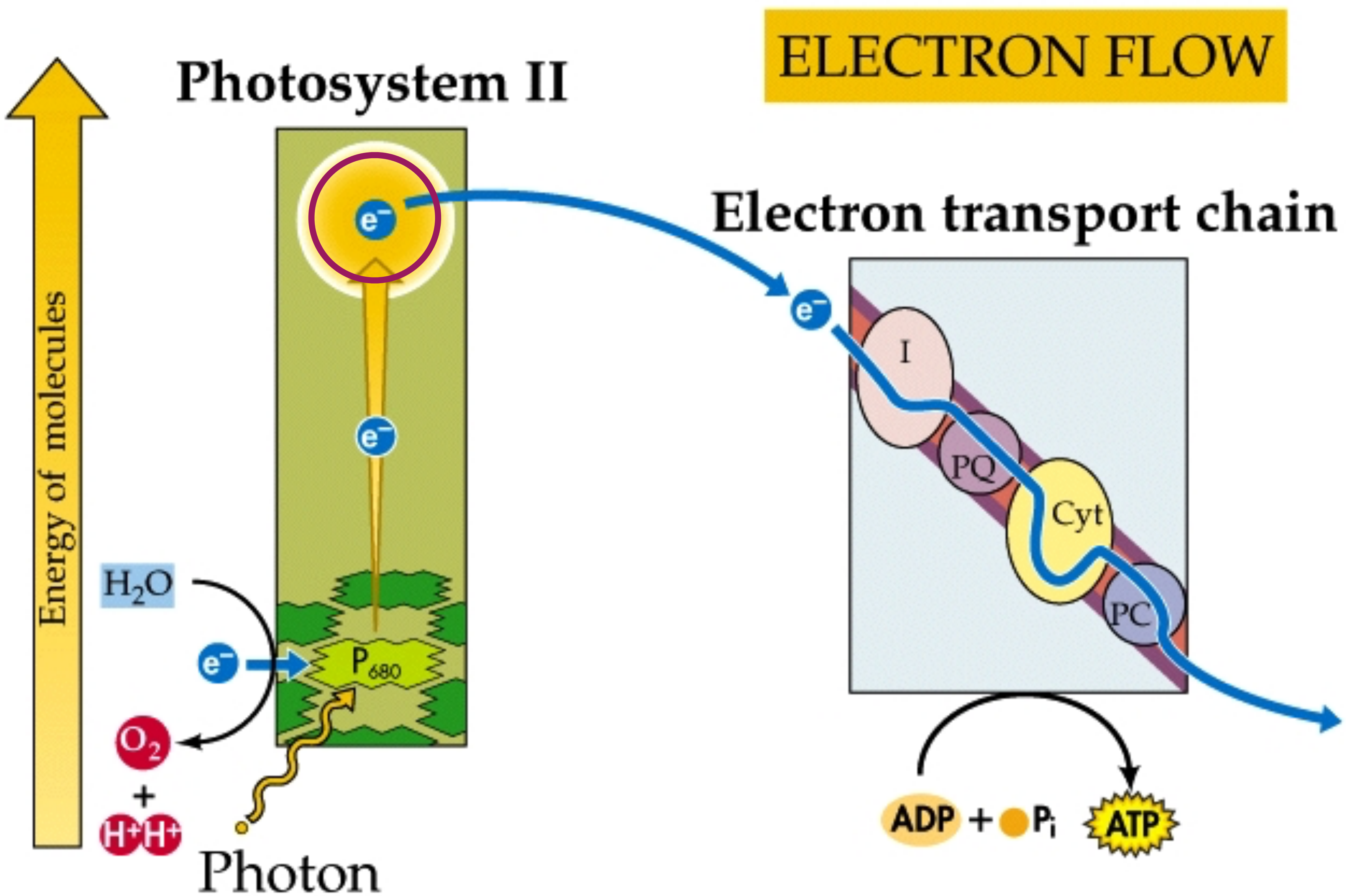

Photosystem II
ELECTRON FLOW
Electron transport chain
Energy of molecules
e−
H2O
O2
+
H+H+
Photon
I
PQ
Cyt
PC
ADP + Pi
ATP


ELECTRON FLOW
Photosystem II
Electron transport chain
Photosystem I
Energy of molecules
e⁻
Fd
NADP+ reductase
H_2O
P_{680}
I
PQ
Cyt
PC
P_{700}
$NADP^+$ + H^+ H^+
NADPH + H^+
O_2 + H^+ H^+
Photon
ADP + P_i
ATP
Photon
© 2001 Sinauer Associates, Inc.
© 2001 Sinauer Associates, Inc.

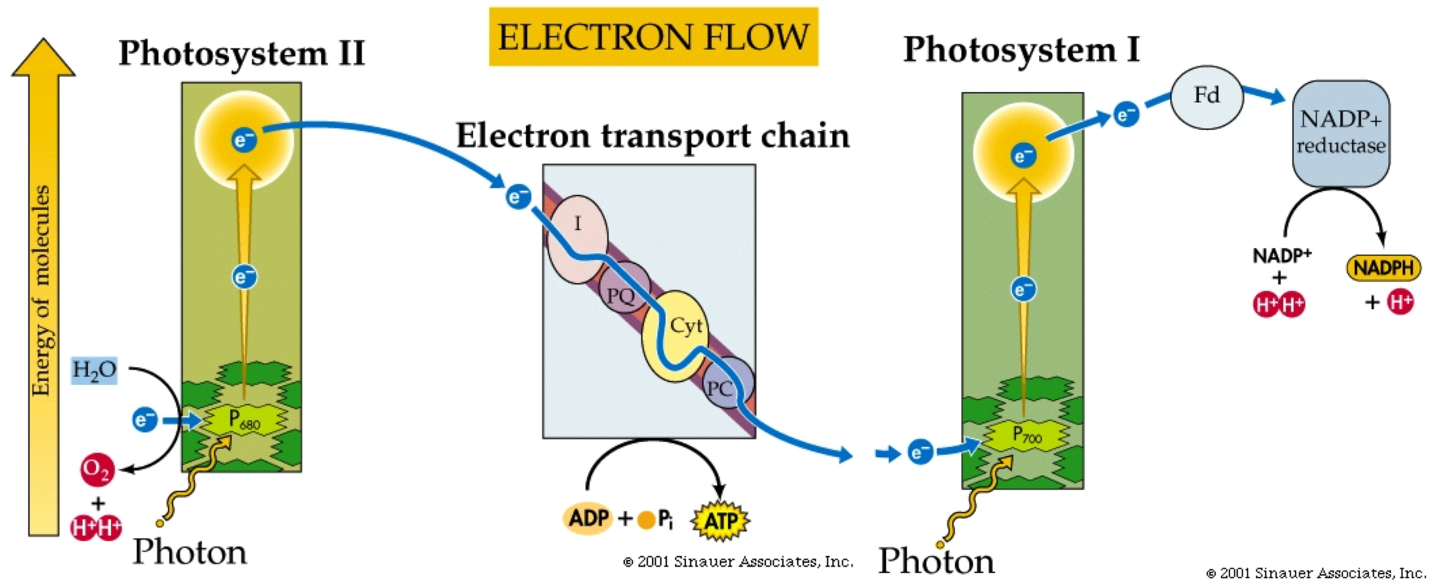

Photosystem II
ELECTRON FLOW
Electron transport chain
Energy of molecules
e⁻
H_2O
P_{680}
O_2
+
H^+ H^+
Photon
I
PQ
Cyt
PC
ADP + P_i
ATP



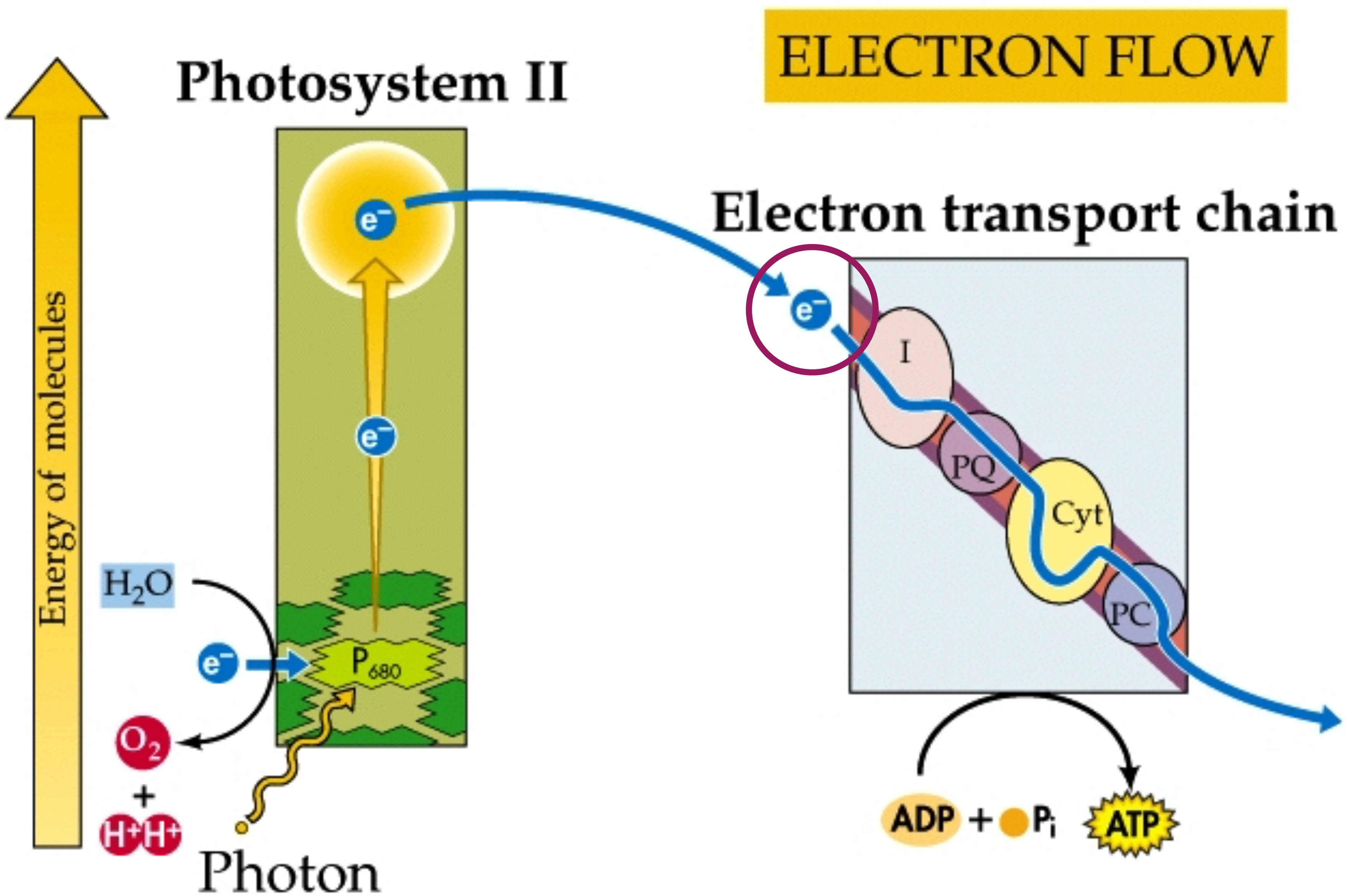
ELECTRON FLOW
Photosystem II
Electron transport chain
Photosystem I
Energy of molecules
H_2O
O_2
+
$H^+ H^+$
Photon
P_{680}
I
PQ
Cyt
PC
ADP + P_i
ATP
© 2001 Sinauer Associates, Inc.
Photon
P_{700}
Fd
NADP+ reductase
$NADP^+$
+
$H^+ H^+$
NADPH
+ H^+
© 2001 Sinauer Associates, Inc.



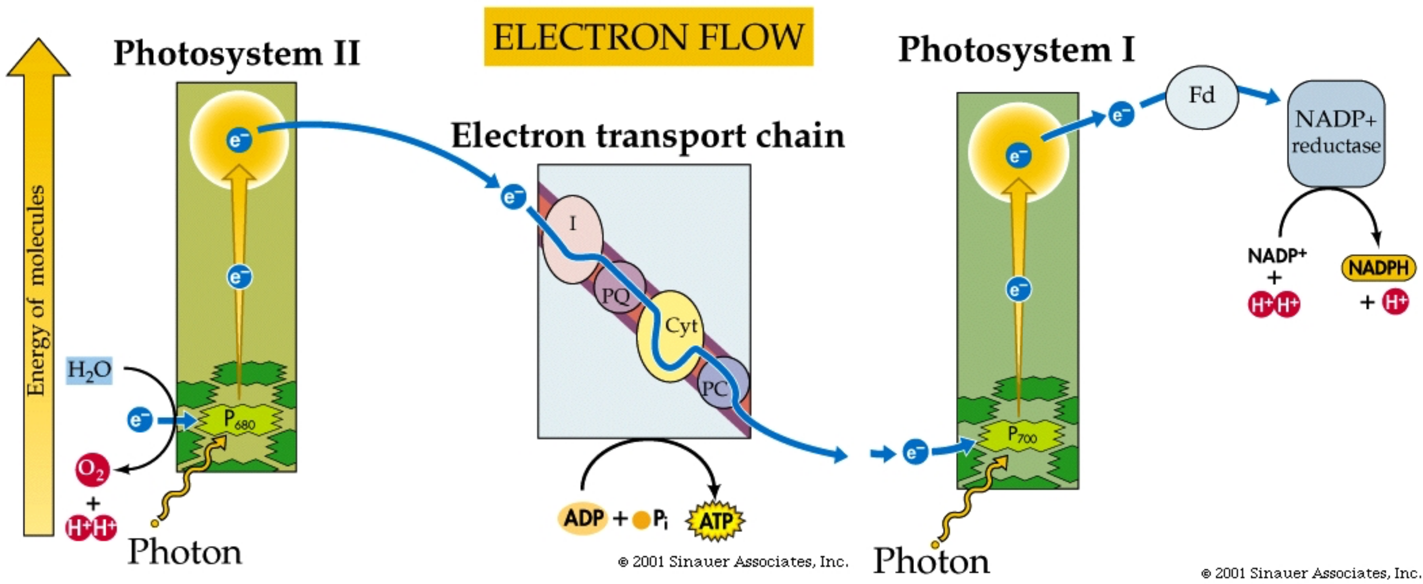
ELECTRON FLOW
Photosystem II
Electron transport chain
Energy of molecules
H_2O
O_2
+
$H^+ H^+$
Photon
P_{680}
I
PQ
Cyt
PC
ADP + P_i
ATP



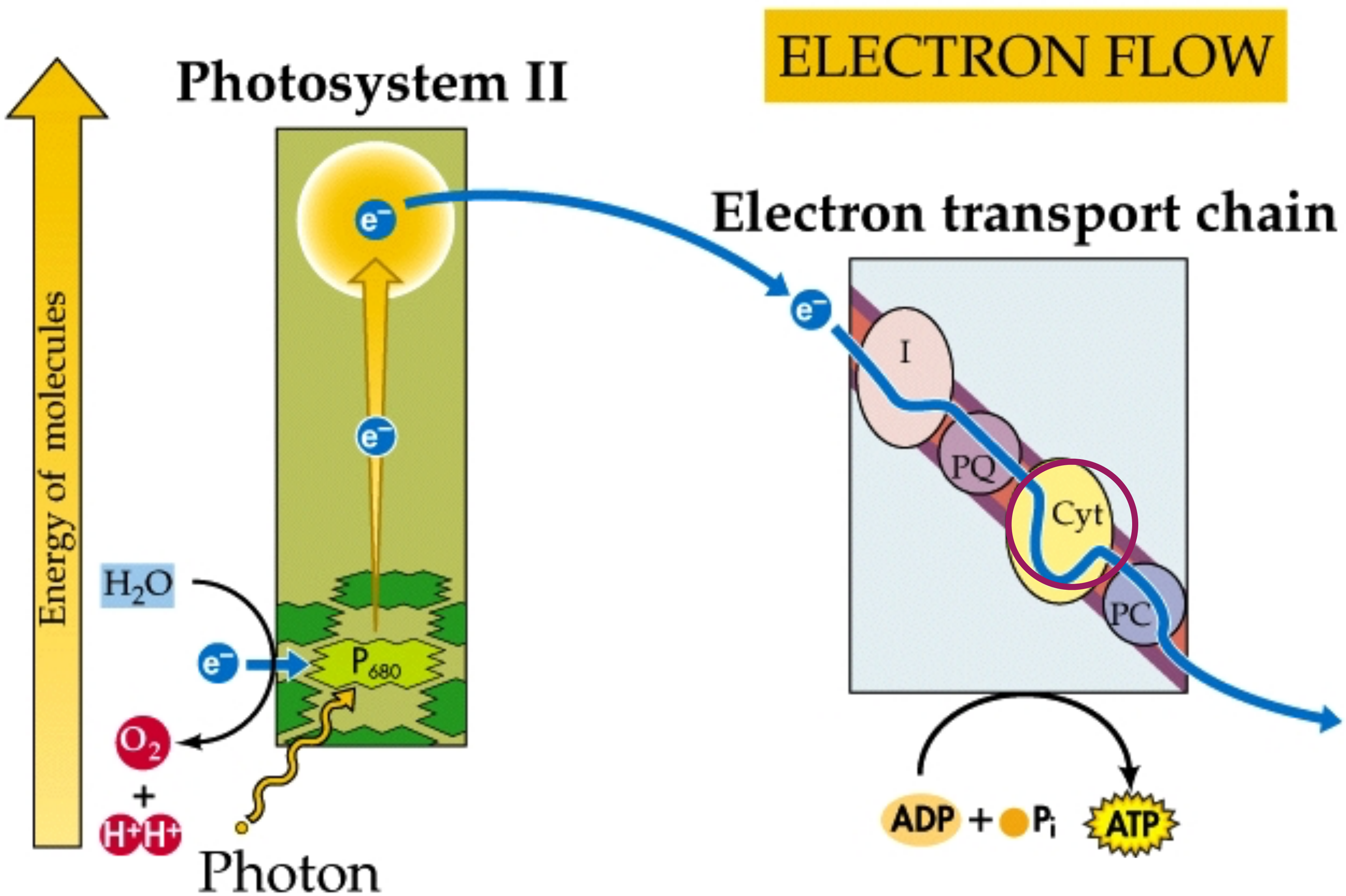
ELECTRON FLOW
Photosystem II
Electron transport chain
Photosystem I
Energy of molecules
H_2O
O_2
+
H^+H^+
Photon
P_{680}
I
PQ
Cyt
PC
ADP + P_i
ATP
© 2001 Sinauer Associates, Inc.
Photon
P_{700}
Fd
NADP+ reductase
$NADP^+$
+
H^+H^+
NADPH
+ H^+
© 2001 Sinauer Associates, Inc.



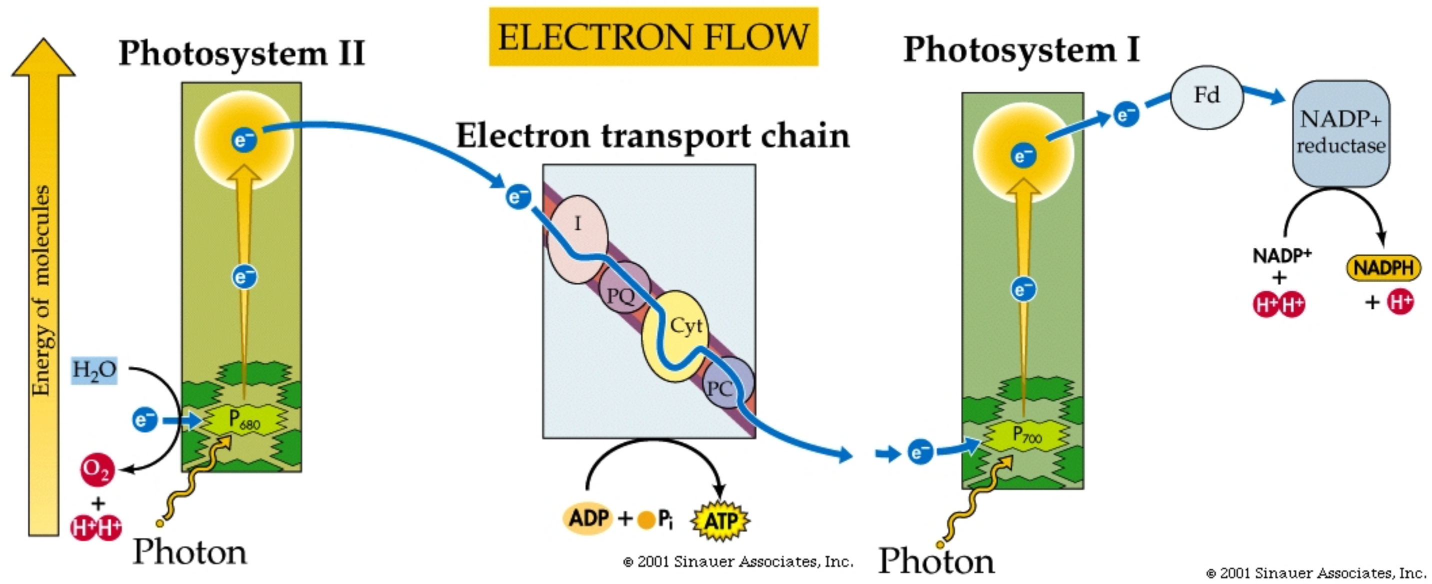
ELECTRON FLOW
Photosystem II
Electron transport chain
Energy of molecules
H_2O
O_2
+
H^+H^+
Photon
P_{680}
I
PQ
Cyt
PC
ADP + P_i
ATP



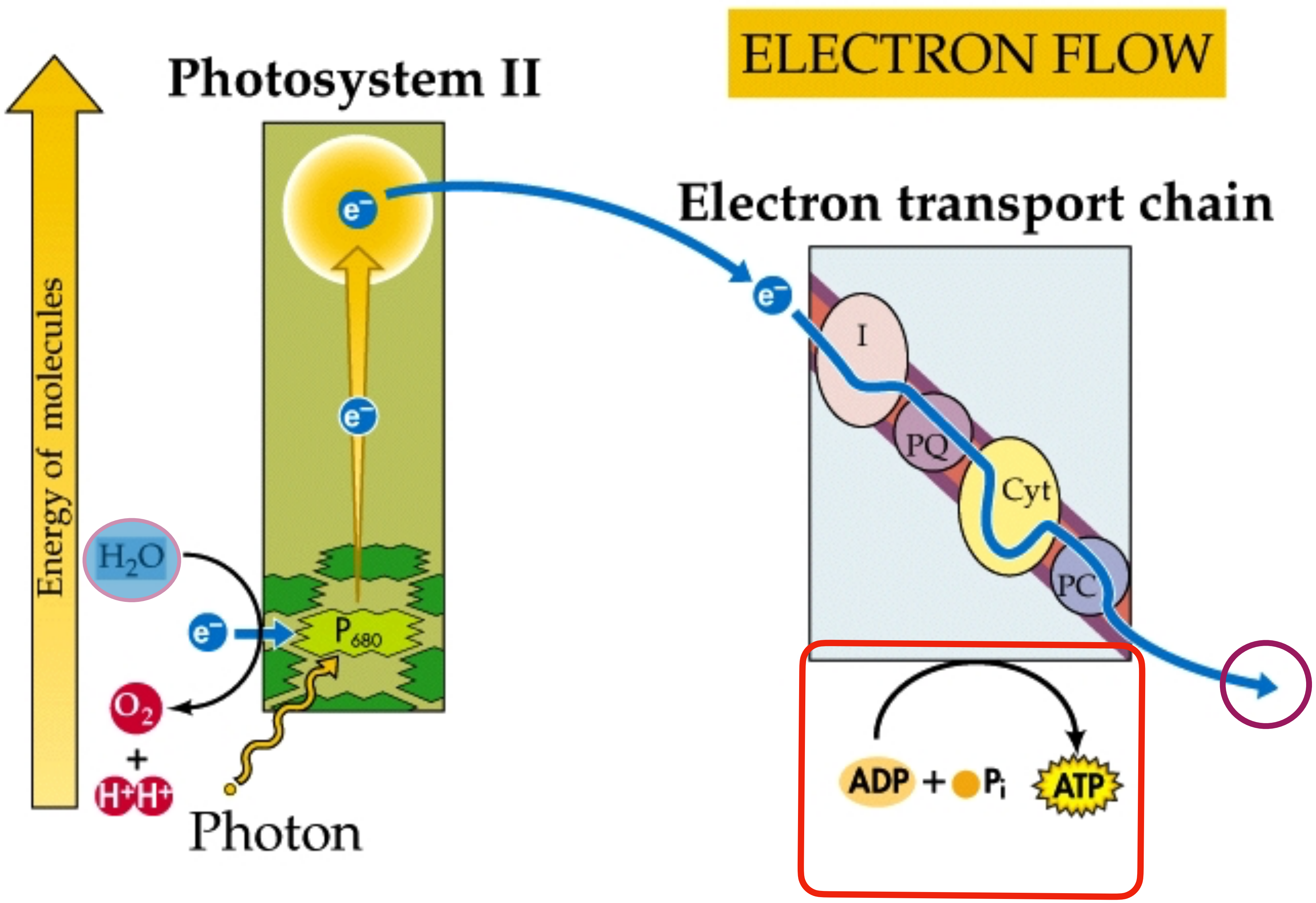
ELECTRON FLOW
Photosystem II
Electron transport chain
Photosystem I
Energy of molecules
H_2O
e^-
O_2
+
H^+H^+
P_{680}
Photon
I
PQ
Cyt
PC
ADP + P_i
ATP
© 2001 Sinauer Associates, Inc.
P_{700}
Fd
NADP+ reductase
$NADP^+$
+
H^+H^+
NADPH
+ H^+
© 2001 Sinauer Associates, Inc.



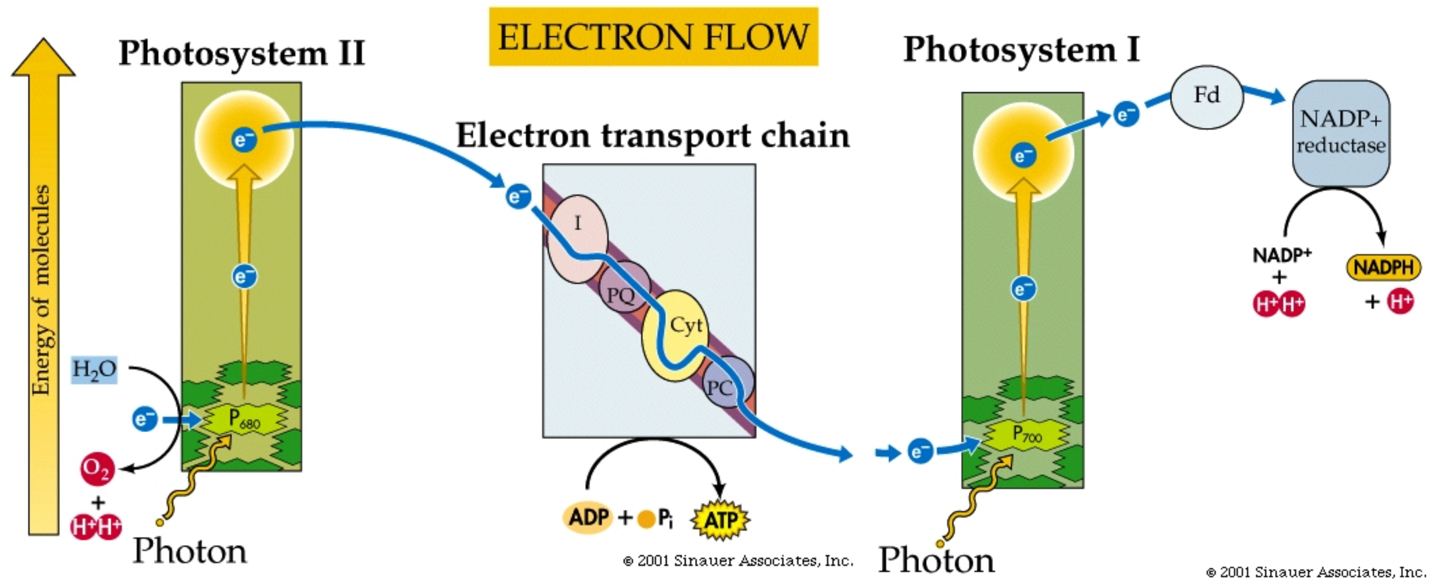
Photosystem II
ELECTRON FLOW
Electron transport chain
Energy of molecules
e^-
H_2O
P_{680}
O_2
+
H^+H^+
Photon
I
PQ
Cyt
PC
ADP + P_i
ATP

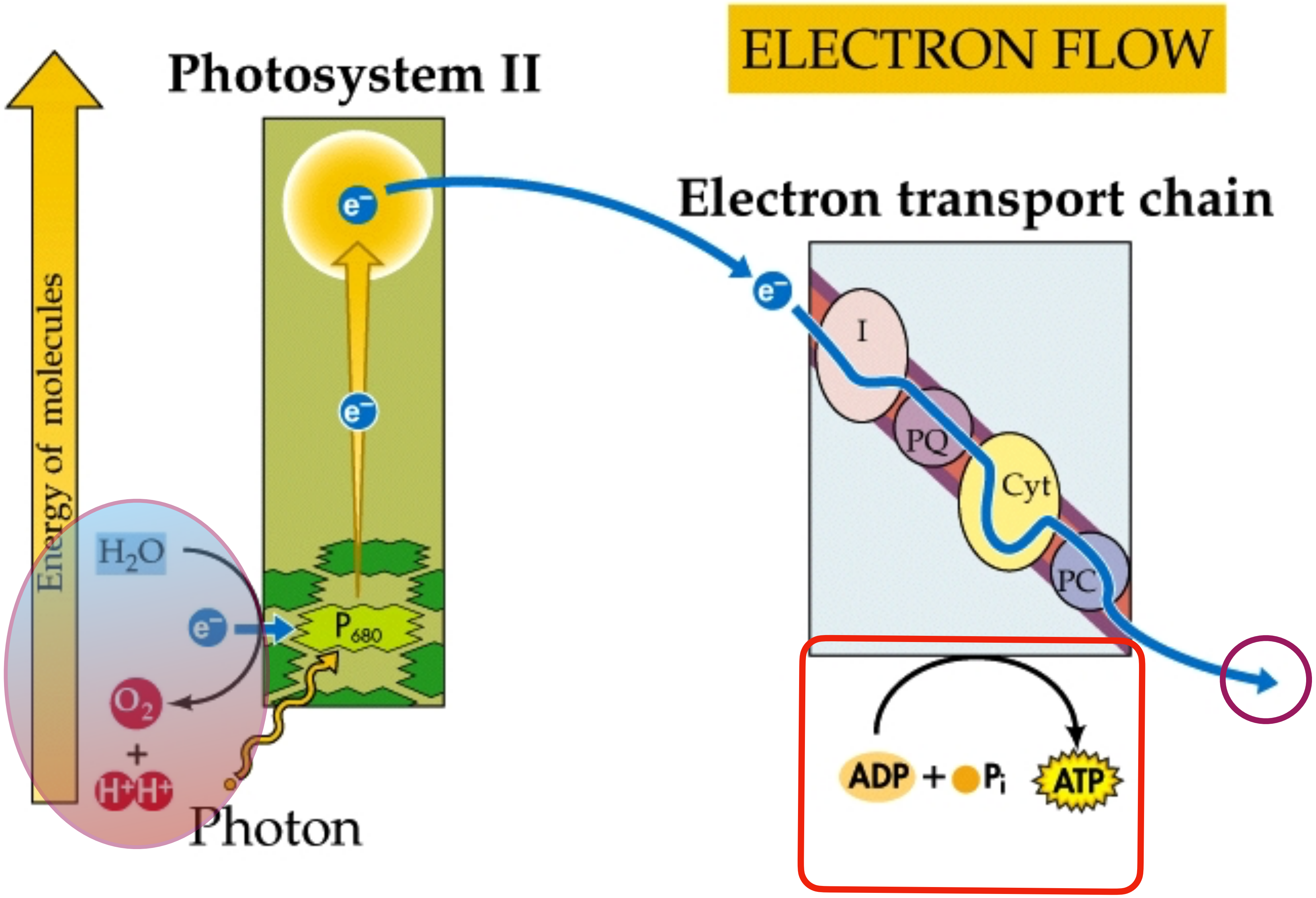


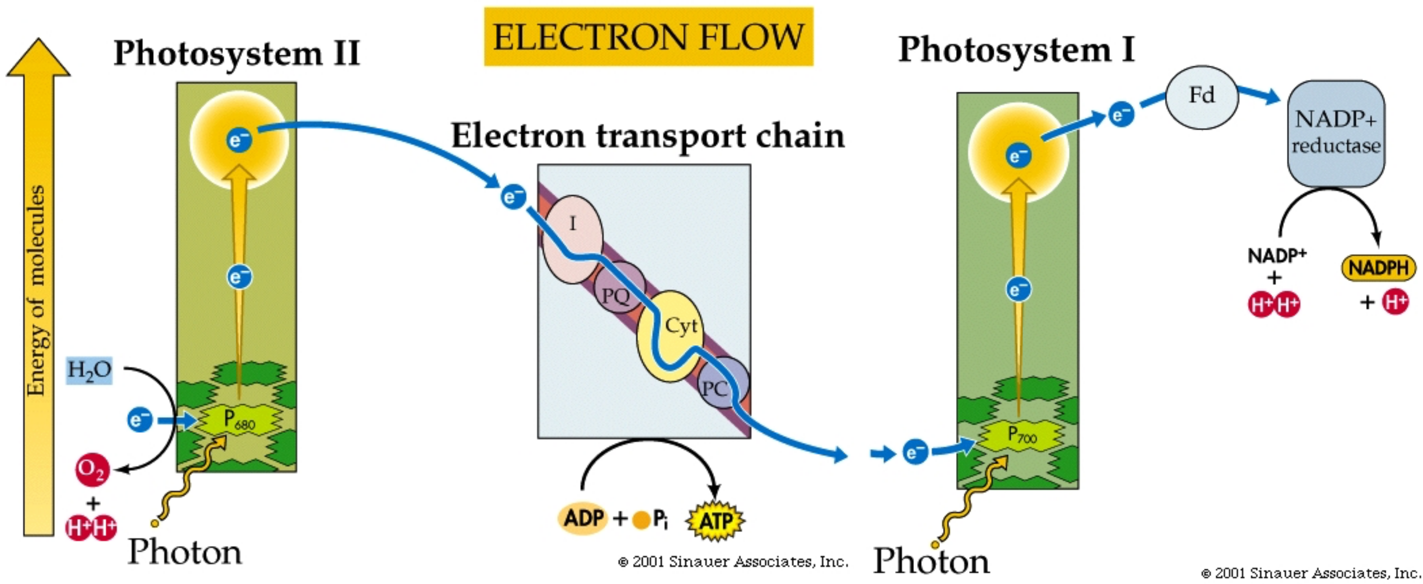
Photosystem II
ELECTRON FLOW
Photosystem I
Electron transport chain
Energy of molecules
H2O
e⁻
O2
+
H+H+
Photon
P680
I
PQ
Cyt
PC
ADP + Pi
ATP
© 2001 Sinauer Associates, Inc.
Photon
P700
Fd
NADP+ reductase
NADP+
+
H+H+
NADPH
+ H+
© 2001 Sinauer Associates, Inc.



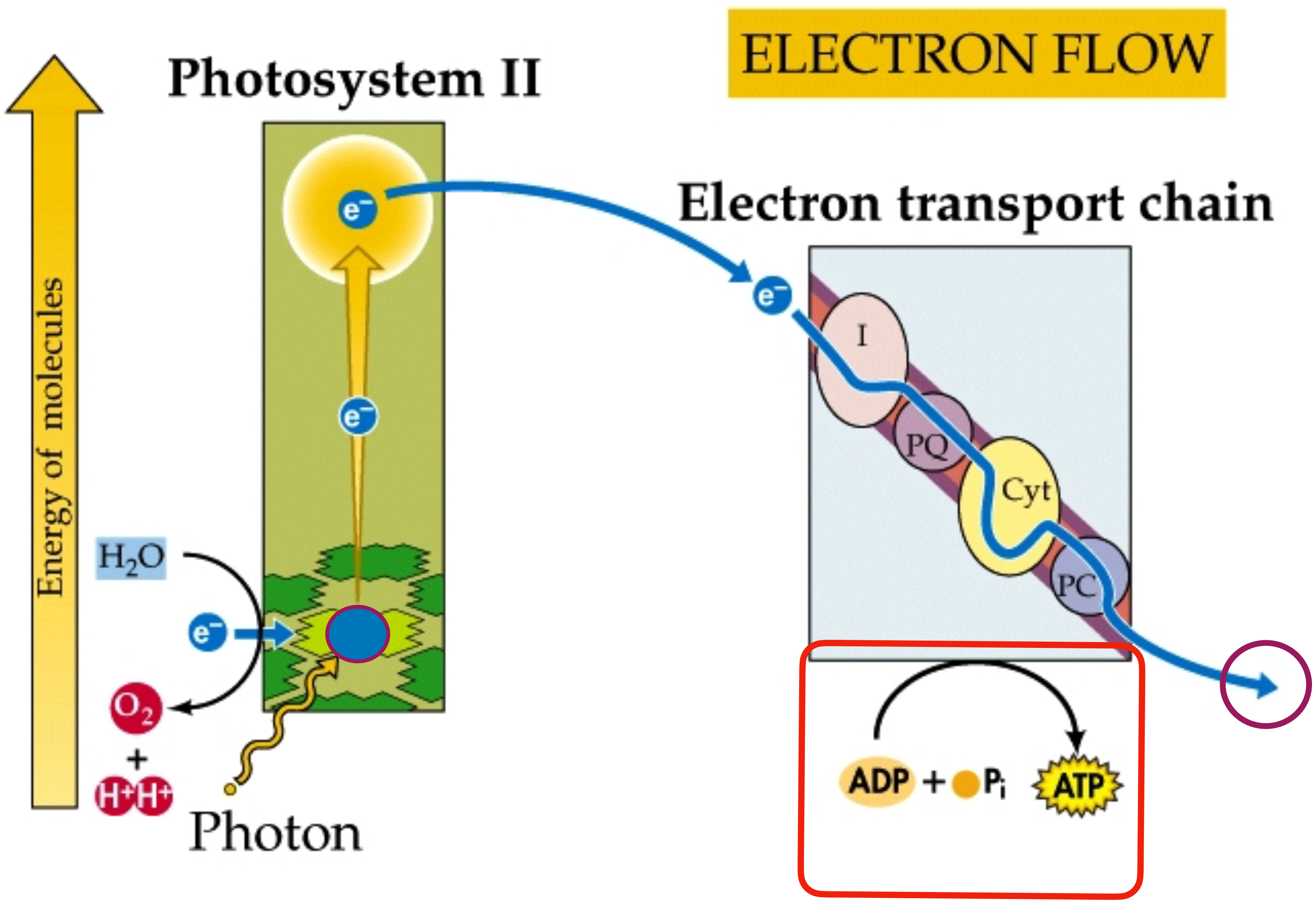
Photosystem II
ELECTRON FLOW
Electron transport chain
Energy of molecules
H2O
e⁻
O2
+
H+H+
Photon
P680
I
PQ
Cyt
PC
ADP + Pi
ATP


ELECTRON FLOW
Photosystem II
Photosystem I
Electron transport chain
Energy of molecules
H_2O
O_2
H^+ H^+
Photon
e⁻
P_{680}
I
PQ
Cyt
PC
ADP + P_i
ATP
P_{700}
Fd
NADP+ reductase
NADP⁺
NADPH
© 2001 Sinauer Associates, Inc.

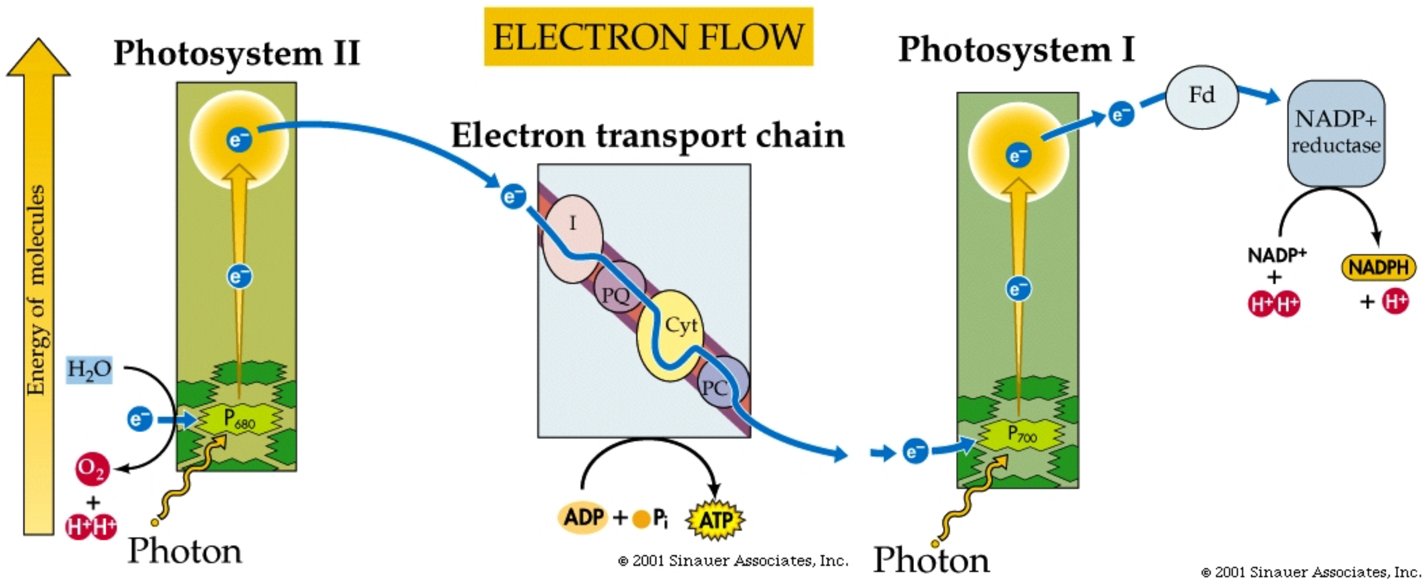

ELECTRON FLOW
Photosystem II
Electron transport chain
Energy of molecules
H_2O
O_2
H^+ H^+
Photon
P_{680}
I
PQ
Cyt
PC
ADP + P_i
ATP

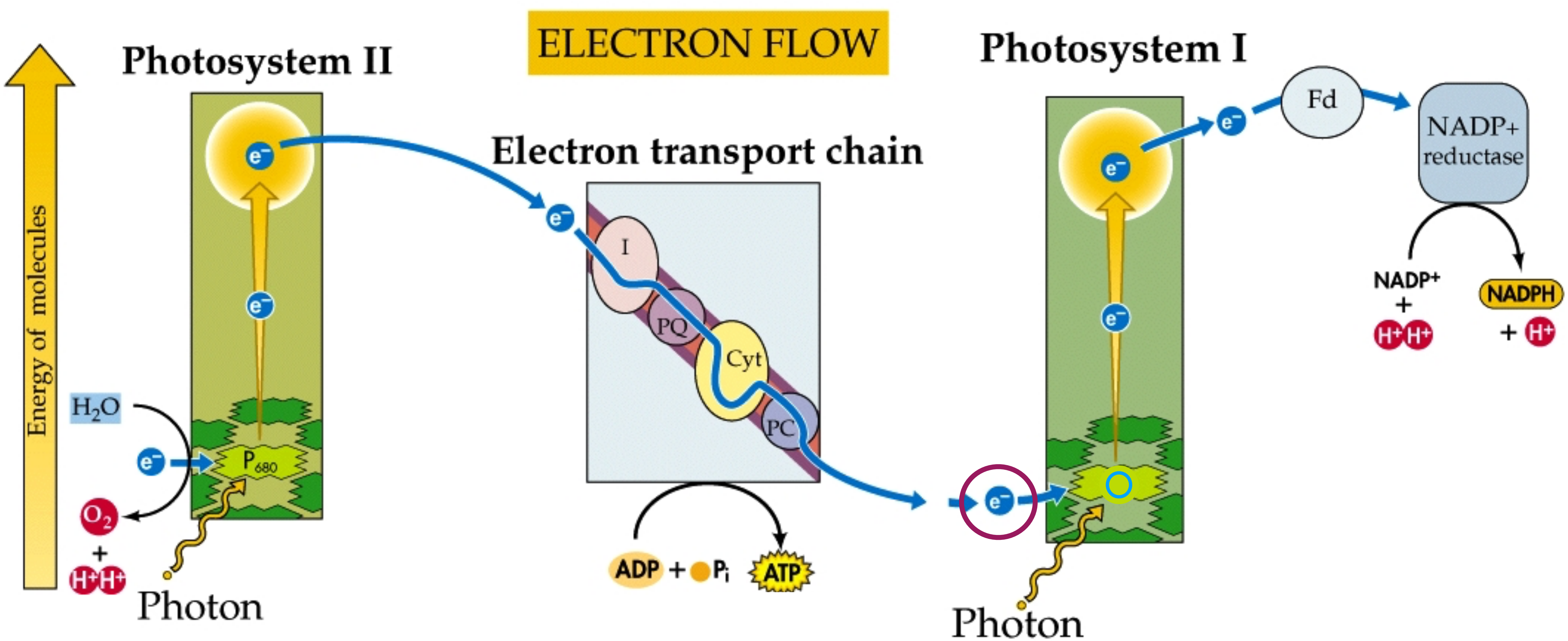


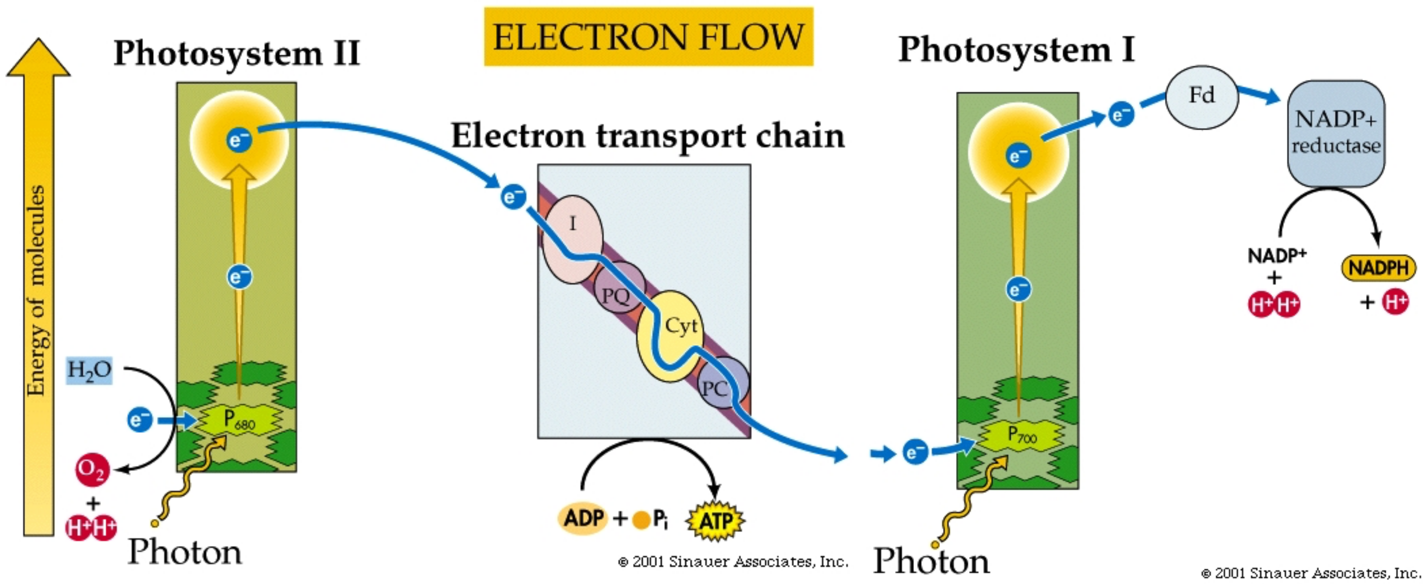
ELECTRON FLOW
Photosystem II
Photosystem I
Electron transport chain
Energy of molecules
H_2O
e⁻
P_{680}
O_2
+
H⁺ H⁺
Photon
I
PQ
Cyt
PC
ADP + P_i
ATP
© 2001 Sinauer Associates, Inc.
Photon
P_{700}
Fd
NADP+ reductase
NADP⁺
+
H⁺ H⁺
NADPH
+ H⁺
© 2001 Sinauer Associates, Inc.



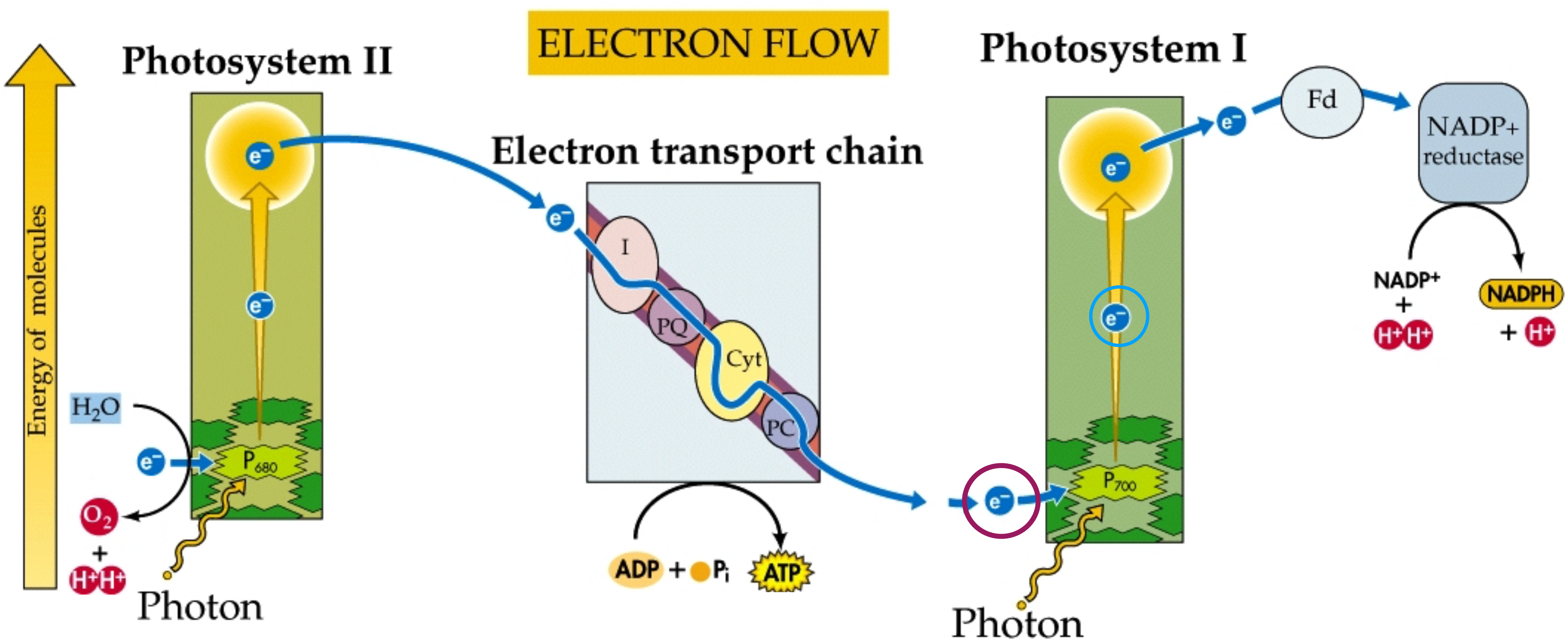
ELECTRON FLOW
Photosystem II
Electron transport chain
Energy of molecules
H_2O
e⁻
O_2
+
H⁺ H⁺
Photon
I
PQ
Cyt
PC
ADP + P_i
ATP


ELECTRON FLOW
Photosystem II
Electron transport chain
Photosystem I
Energy of molecules
H_2O
O_2
H^+ H^+
P_{680}
Photon
I
PQ
Cyt
PC
ADP + P_i
ATP
P_{700}
Fd
NADP+ reductase
NADP+
NADPH
© 2001 Sinauer Associates, Inc.
© 2001 Sinauer Associates, Inc.

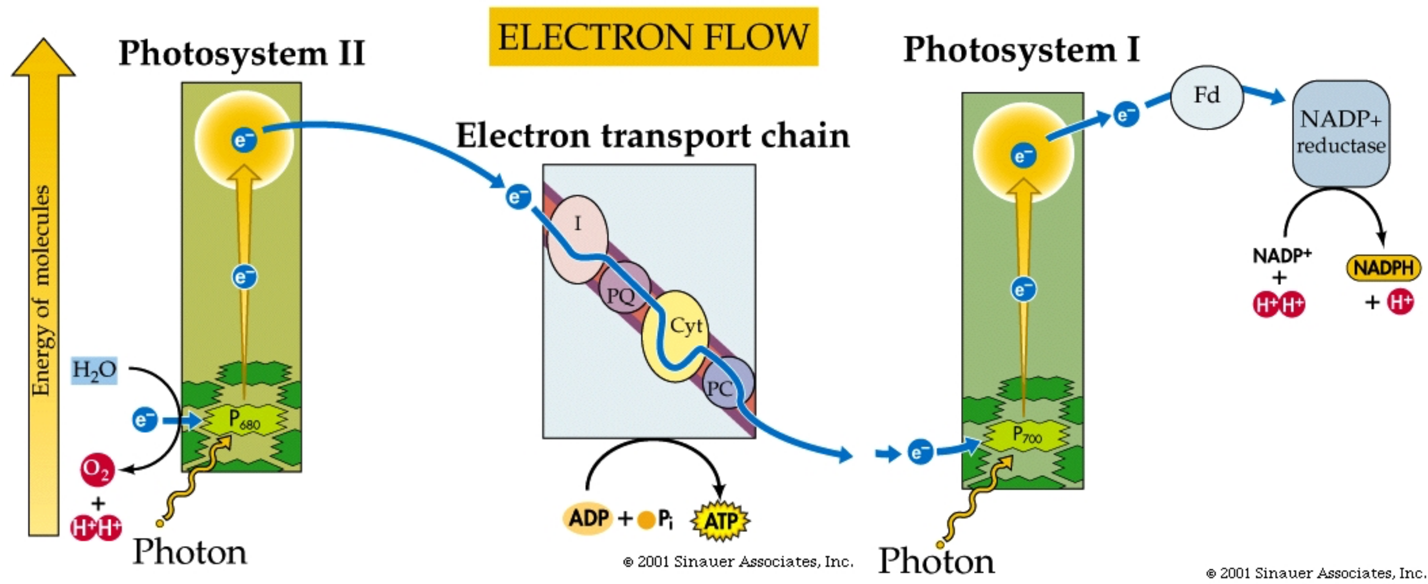

ELECTRON FLOW
Photosystem II
Electron transport chain
Photosystem I
Energy of molecules
H_2O
O_2
H^+ H^+
P_{680}
Photon
I
PQ
Cyt
PC
ADP + P_i
ATP
Photon
Fd
NADP+ reductase
NADP+
NADPH

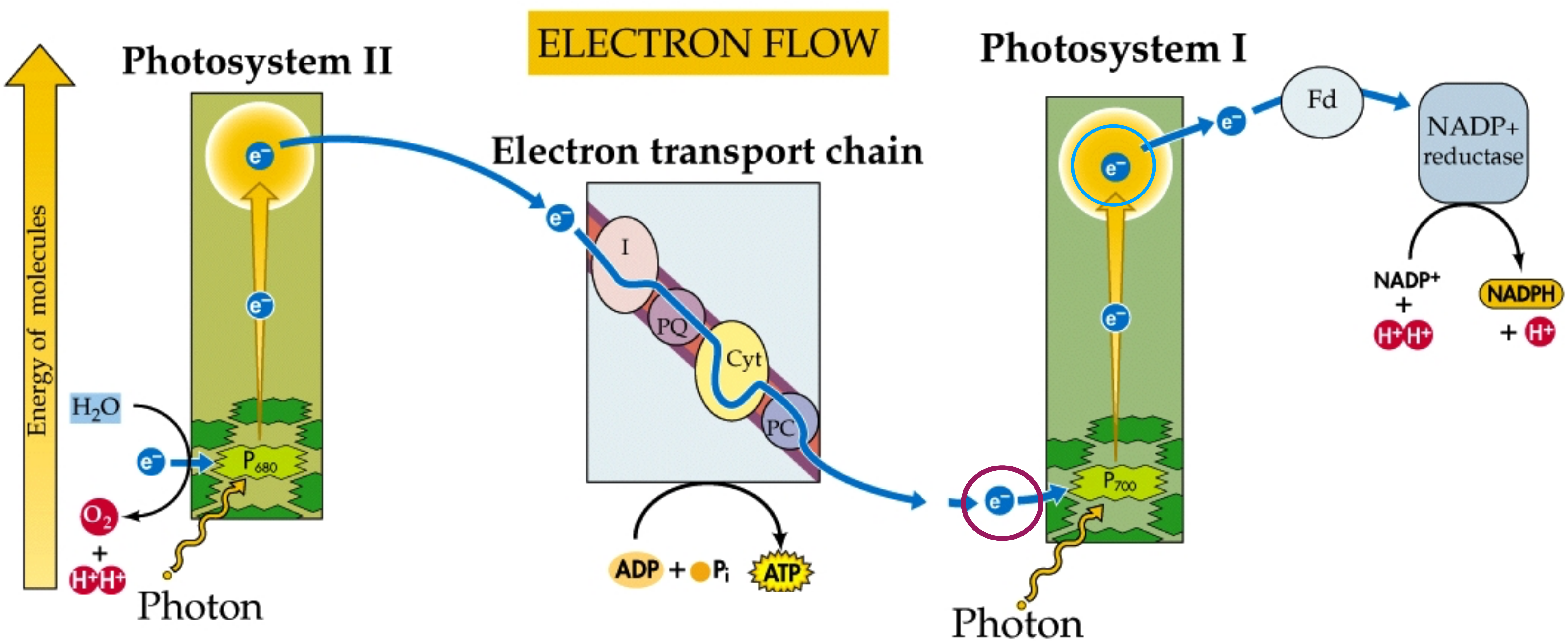


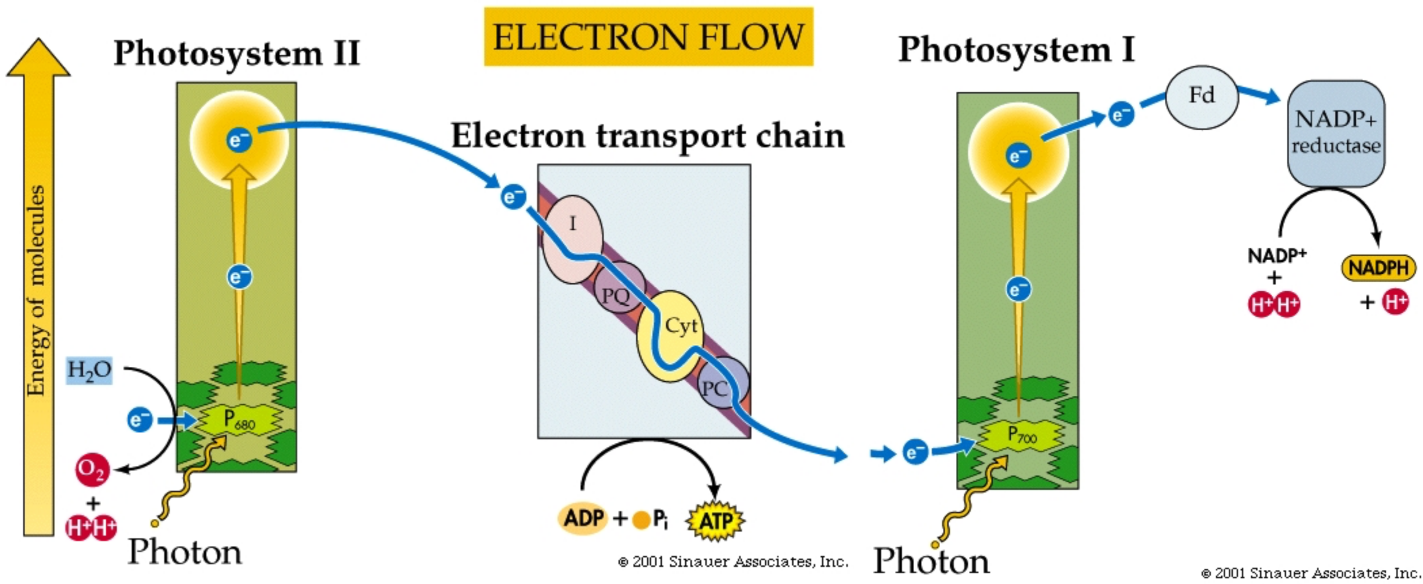
ELECTRON FLOW
Photosystem II
Electron transport chain
Photosystem I
Energy of molecules
e⁻
H2O
O2
+
H+ H+
P680
Photon
I
PQ
Cyt
PC
ADP + Pi
ATP
© 2001 Sinauer Associates, Inc.
P700
Fd
NADP+ reductase
NADP+
+
H+ H+
NADPH
+ H+
© 2001 Sinauer Associates, Inc.

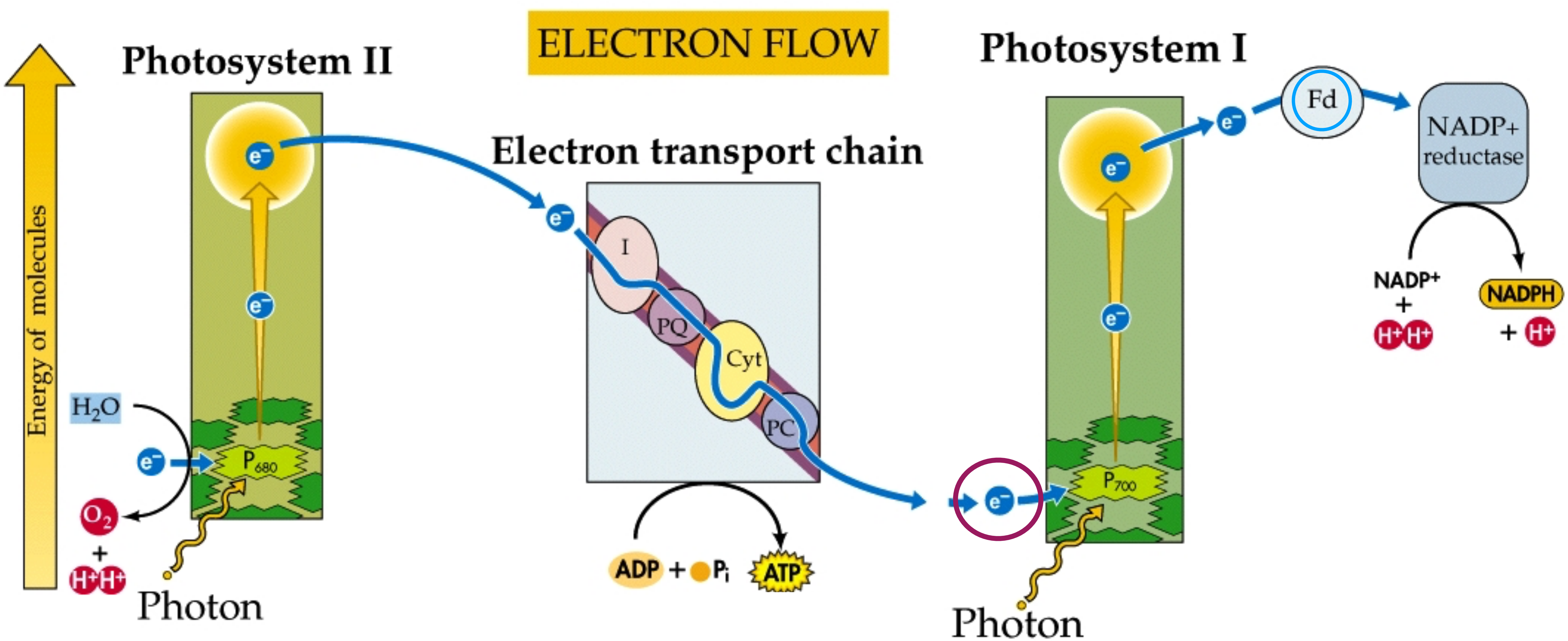


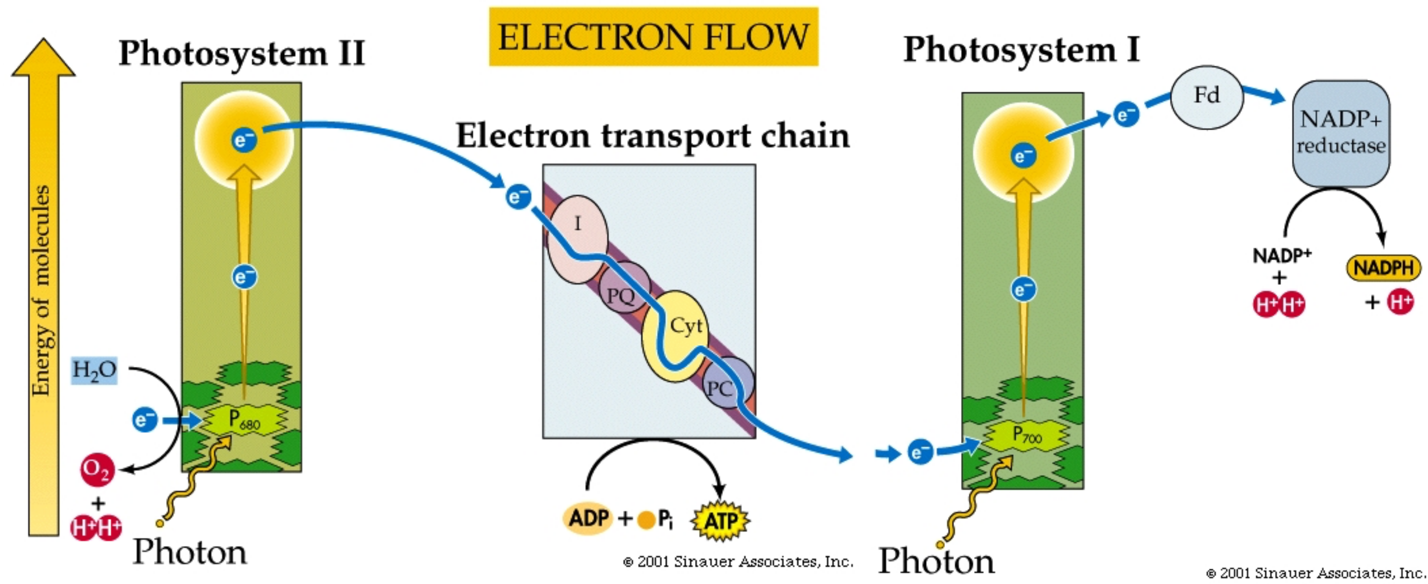
ELECTRON FLOW
Photosystem II
Electron transport chain
Photosystem I
Energy of molecules
e⁻
H2O
O2
+
H+ H+
P680
Photon
I
PQ
Cyt
PC
ADP + Pi
ATP
P700
Photon
Fd
NADP+ reductase
NADP+
+
H+ H+
NADPH
+ H+


ELECTRON FLOW
Photosystem II
Electron transport chain
Photosystem I
Energy of molecules
H2O
O2
+
H+H+
Photon
P680
e−
I
PQ
Cyt
PC
ADP + Pi
ATP
© 2001 Sinauer Associates, Inc.
Photon
P700
Fd
NADP+ reductase
NADP+
+
H+H+
NADPH
+ H+
© 2001 Sinauer Associates, Inc.

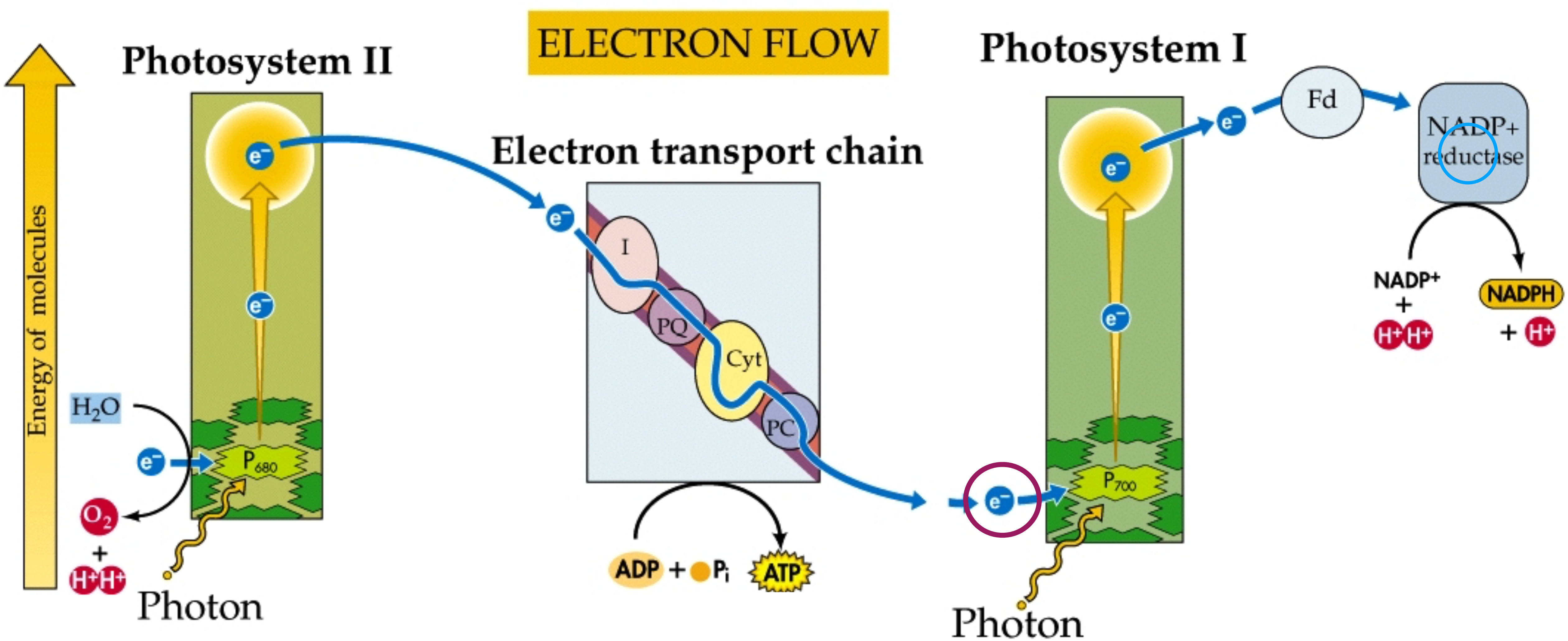

ELECTRON FLOW
Photosystem II
Electron transport chain
Photosystem I
Energy of molecules
H2O
O2
+
H+H+
Photon
P680
e−
I
PQ
Cyt
PC
ADP + Pi
ATP
Photon
P700
Fd
NADP+ reductase
NADP+
+
H+H+
NADPH
+ H+


ELECTRON FLOW
Photosystem II
Electron transport chain
Photosystem I
Energy of molecules
e⁻
H_2O
O_2
+
H+ H+
P_{680}
Photon
I
PQ
Cyt
PC
ADP + P_i
ATP
© 2001 Sinauer Associates, Inc.
P_{700}
Photon
Fd
NADP+ reductase
NADP+
+
H+ H+
NADPH
+ H+
© 2001 Sinauer Associates, Inc.

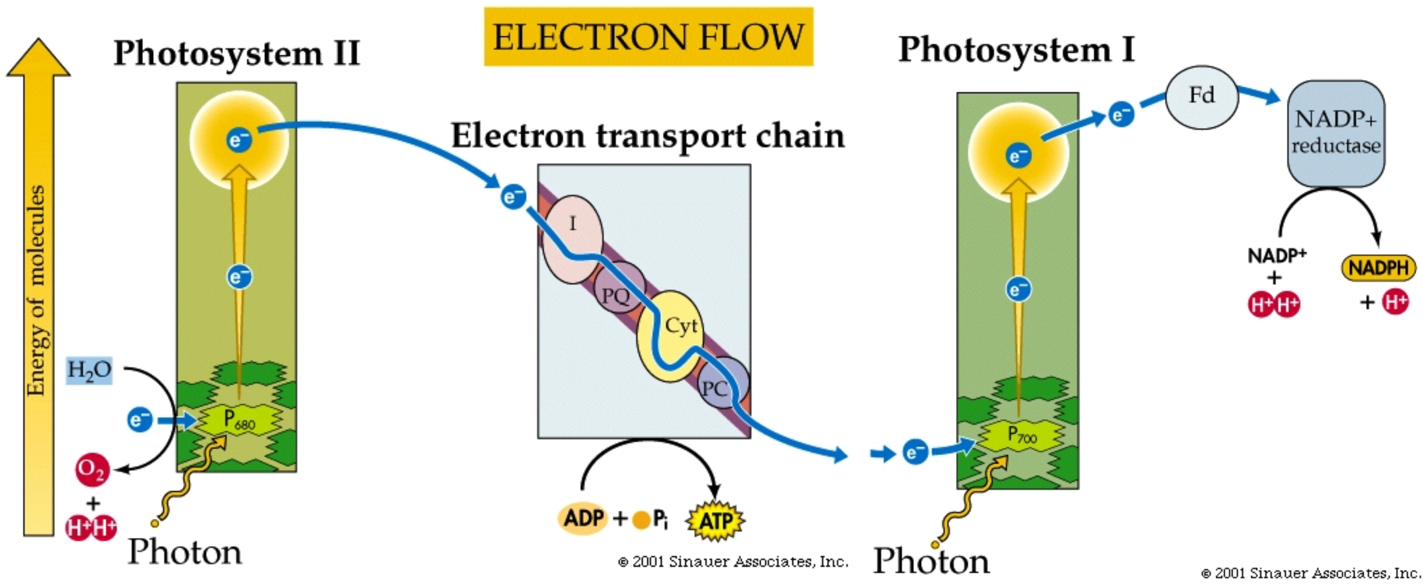

ELECTRON FLOW
Photosystem II
Electron transport chain
Photosystem I
Energy of molecules
e⁻
H_2O
O_2
+
H+ H+
P_{680}
Photon
I
PQ
Cyt
PC
ADP + P_i
ATP
P_{700}
Photon
Fd
NADP+ reductase
NADP+
+
H+ H+
NADPH
+ H+



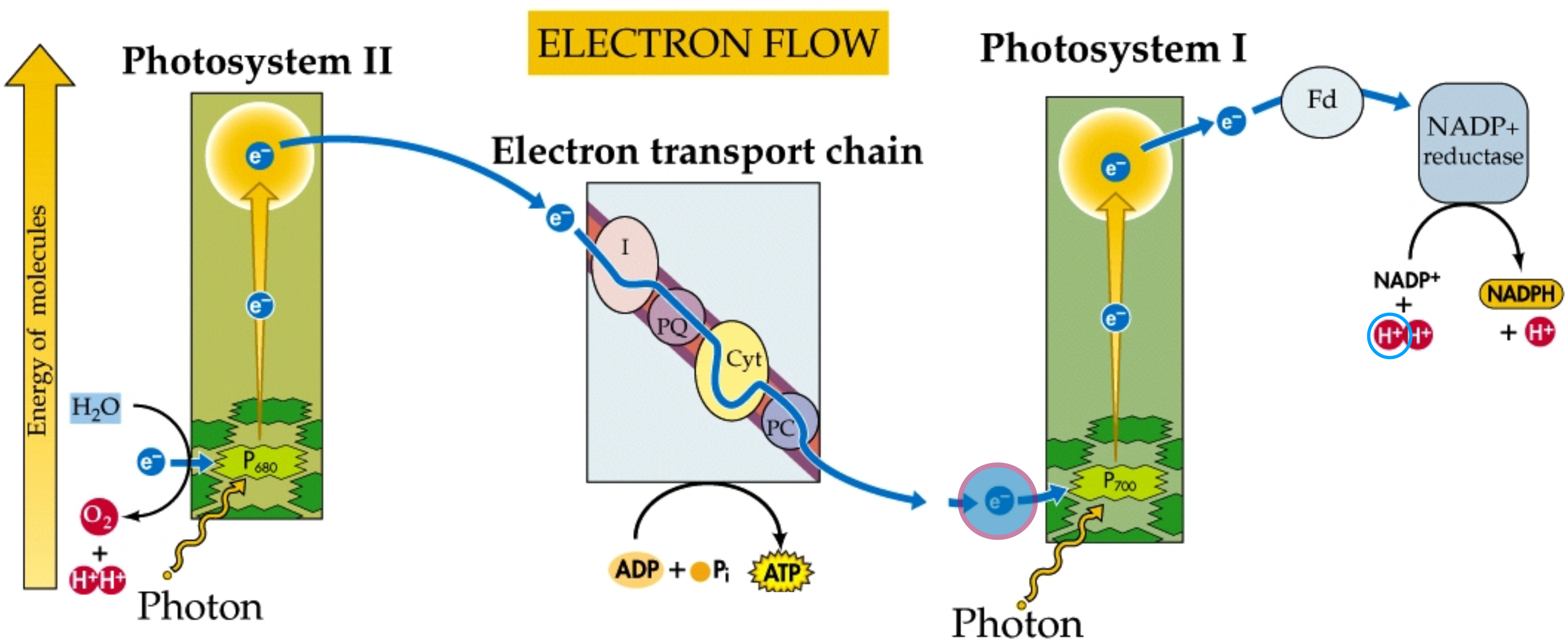
ELECTRON FLOW
Photosystem II
Electron transport chain
Photosystem I
Energy of molecules
H_2O
O_2
+
H+ H+
Photon
P680
I
PQ
Cyt
PC
ADP + Pi
ATP
© 2001 Sinauer Associates, Inc.
Photon
P700
Fd
NADP+ reductase
NADP+
+
H+ H+
NADPH
+ H+
© 2001 Sinauer Associates, Inc.



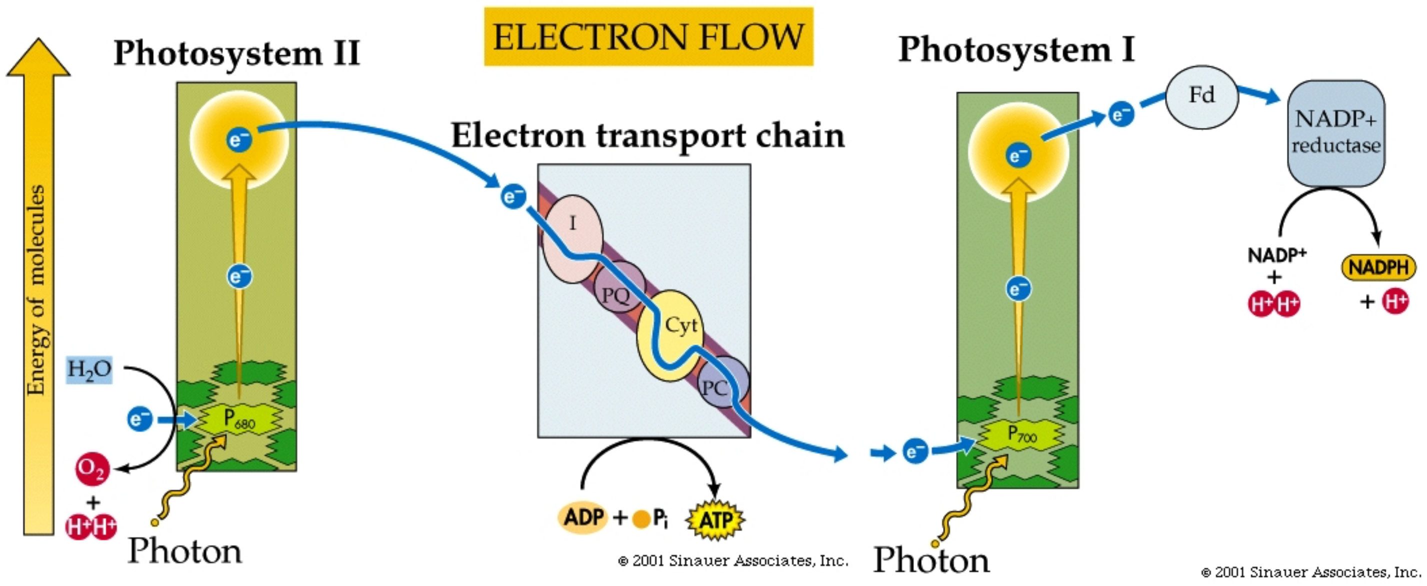
ELECTRON FLOW
Photosystem II
Electron transport chain
Photosystem I
Energy of molecules
H_2O
O_2
+
H+ H+
Photon
P680
I
PQ
Cyt
PC
ADP + Pi
ATP
Photon
P700
Fd
NADP+ reductase
NADP+
+
H+ H+
NADPH
+ H+



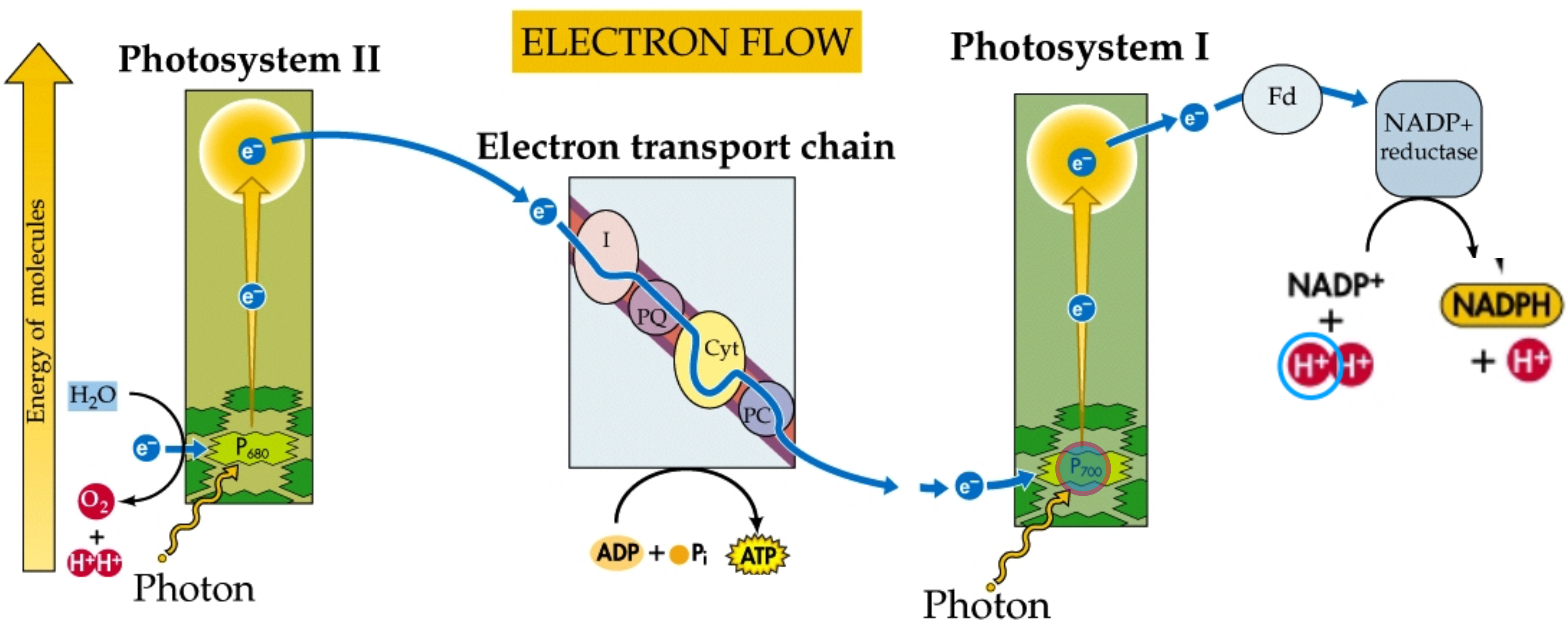
ELECTRON FLOW
Photosystem II
Photosystem I
Electron transport chain
Energy of molecules
H2O
O2
+
H+ H+
Photon
e−
P680
I
PQ
Cyt
PC
ADP + Pi
ATP
P700
Fd
NADP+ reductase
NADP+
+
H+ H+
NADPH
+ H+
© 2001 Sinauer Associates, Inc.
Photon
© 2001 Sinauer Associates, Inc.



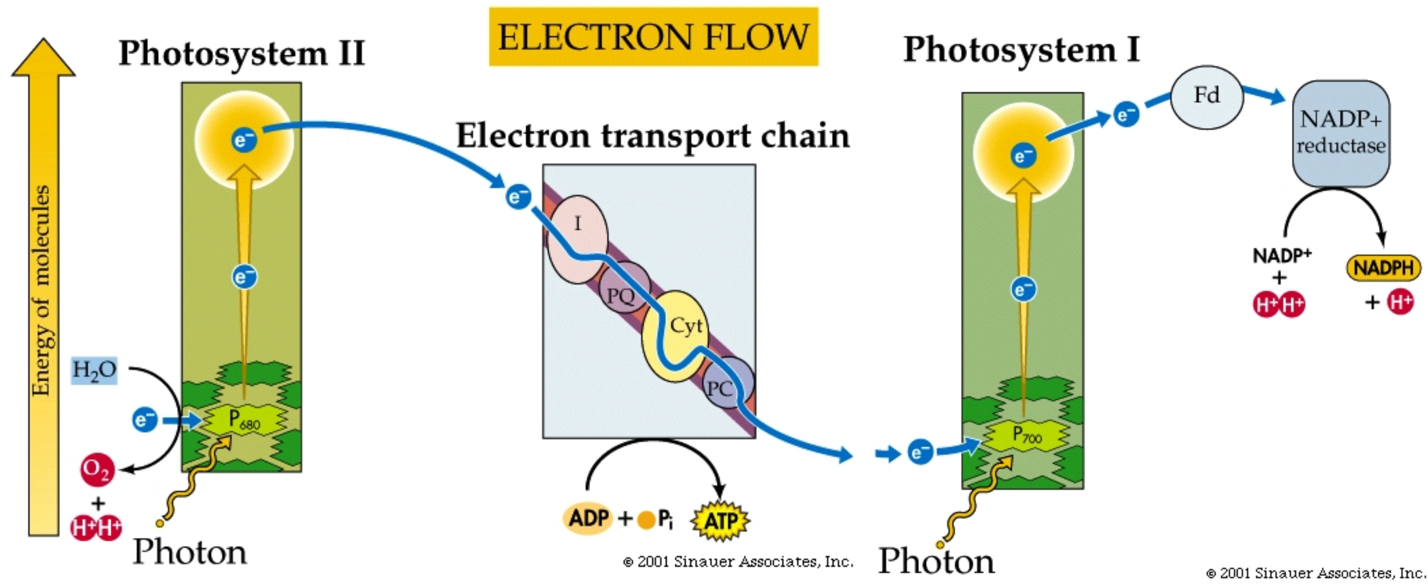
ELECTRON FLOW
Photosystem II
Photosystem I
Electron transport chain
Energy of molecules
H2O
O2
+
H+ H+
Photon
e−
P680
I
PQ
Cyt
PC
ADP + Pi
ATP
P700
Photon
Fd
NADP+ reductase
NADP+
+
H+ H+
NADPH
+ H+

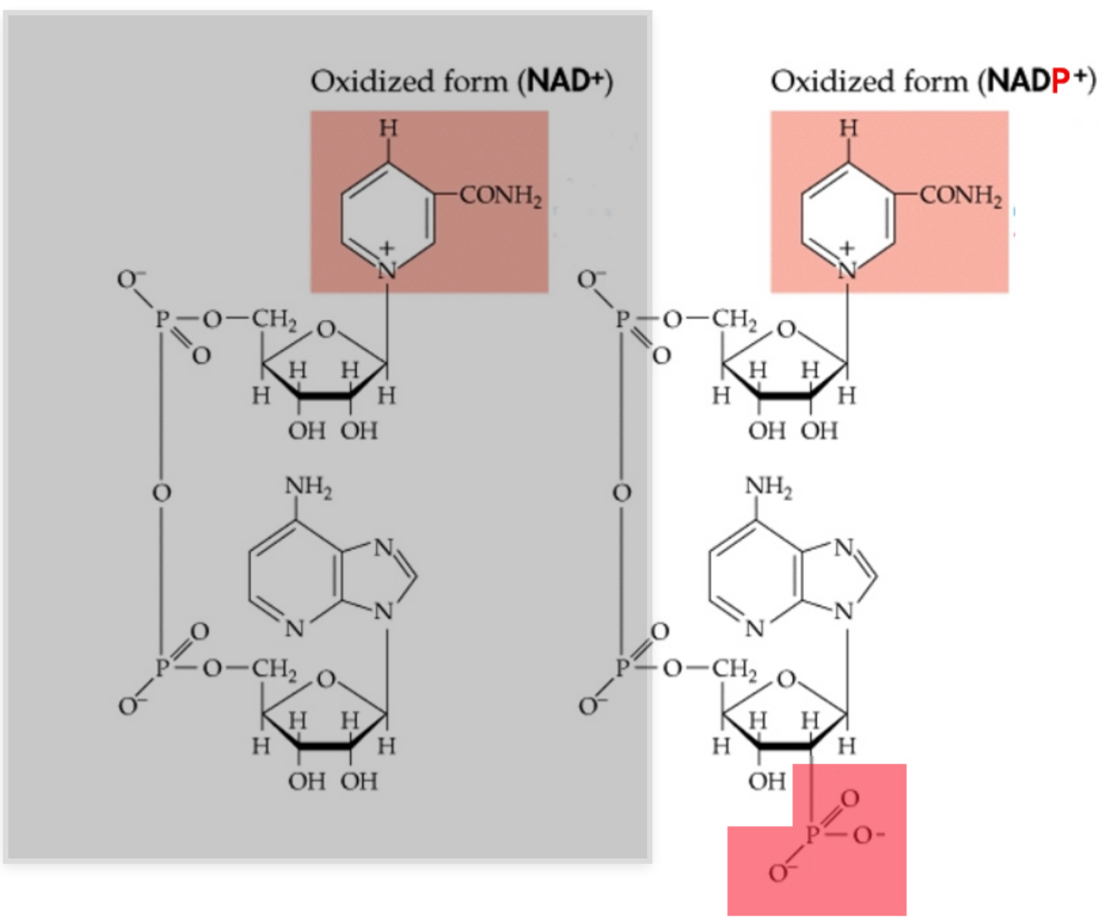


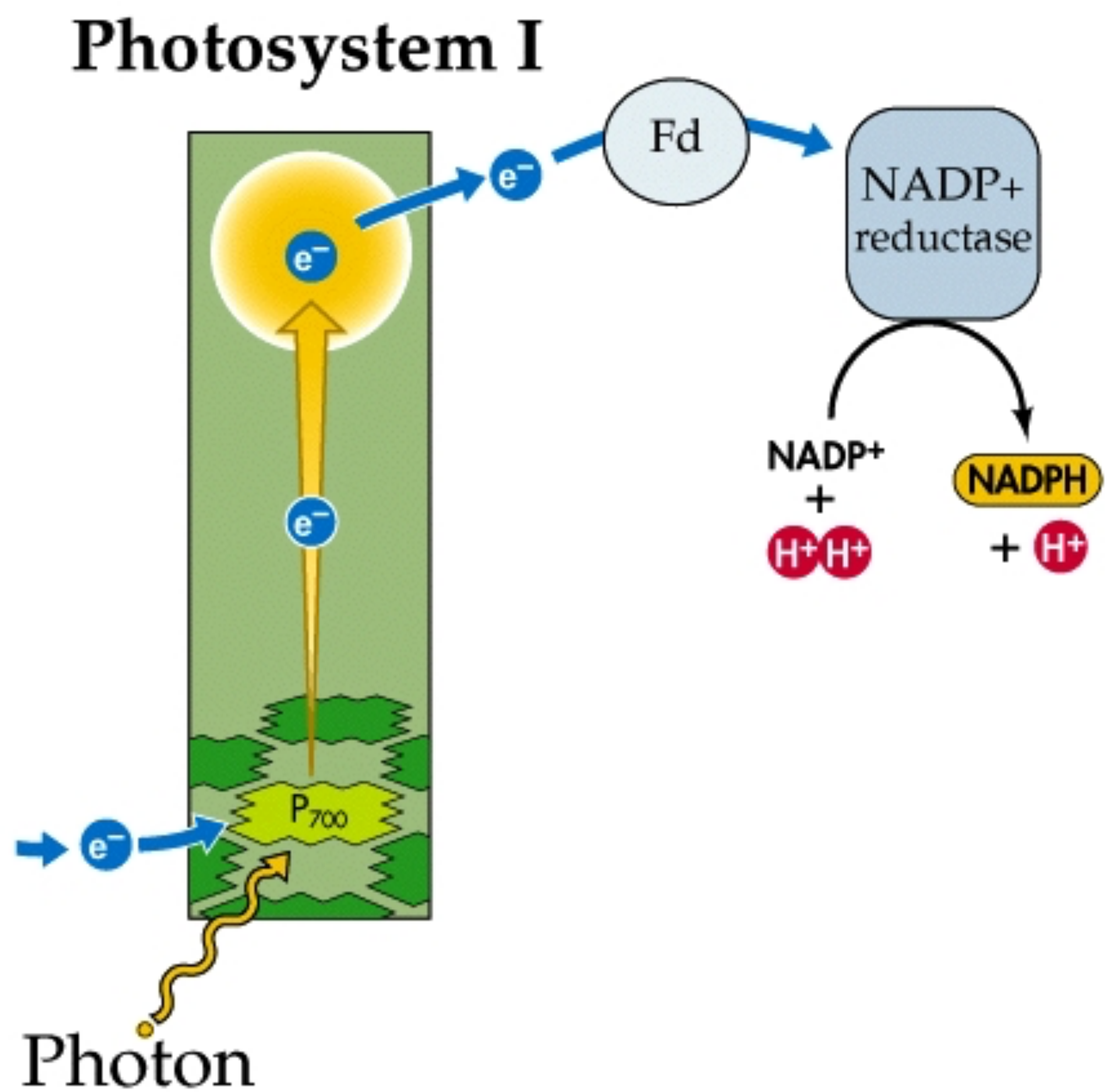
ELECTRON FLOW
Photosystem II
Electron transport chain
Photosystem I
Energy of molecules
H_2O
O_2
+
H+ H+
Photon
P_{680}
I
PQ
Cyt
PC
ADP + P_i
ATP
P_{700}
Fd
NADP+ reductase
NADP+
+
H+ H+
NADPH
+ H+
Photon
© 2001 Sinauer Associates, Inc.
© 2001 Sinauer Associates, Inc.

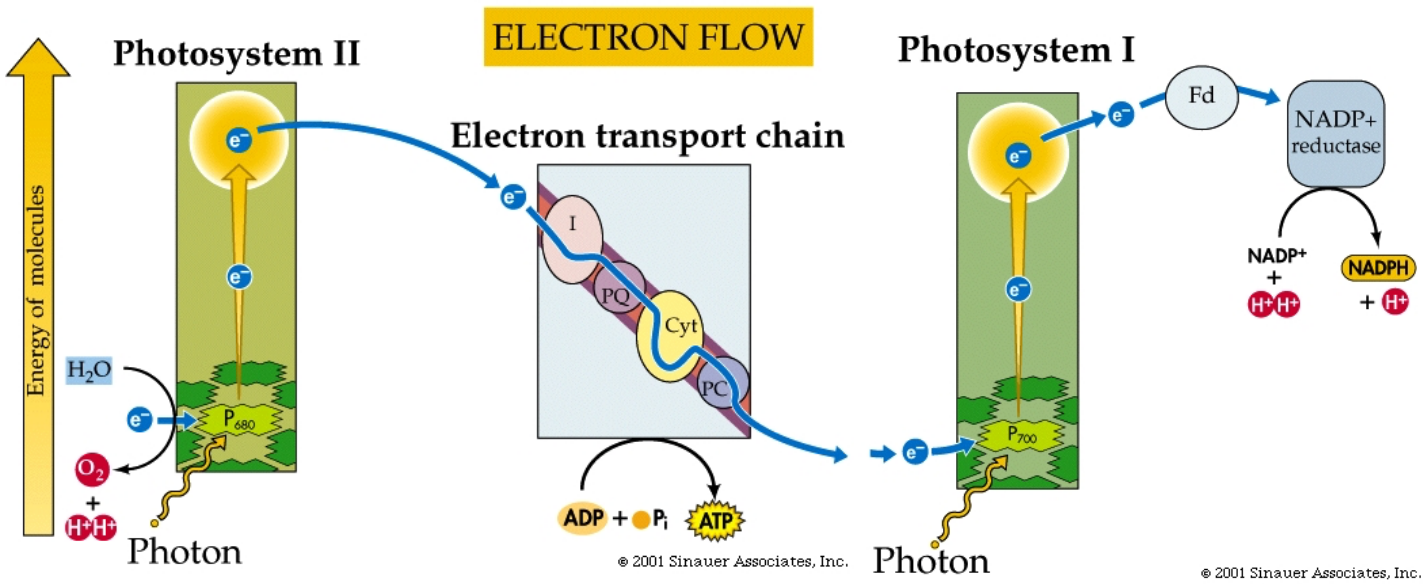


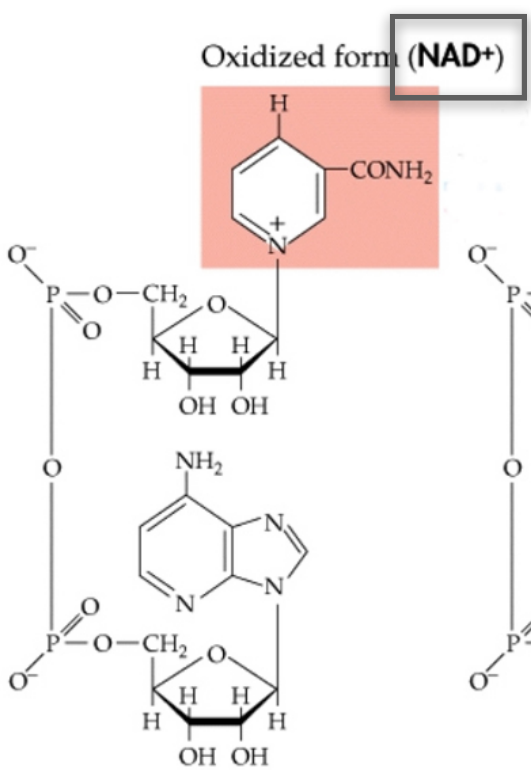
ELECTRON FLOW
Photosystem II
Electron transport chain
Photosystem I
Energy of molecules
H_2O
O_2
+
H+ H+
Photon
P_{680}
I
PQ
Cyt
PC
ADP + P_i
ATP
P_{700}
Fd
NADP+ reductase
NADP+
+
H+ H+
NADPH
+ H+
Photon


ELECTRON FLOW
Photosystem II
Electron transport chain
Photosystem I
Energy of molecules
H_2O
O_2
+
H^+ H^+
P_{680}
Photon
e⁻
I
PQ
Cyt
PC
ADP + P_i
ATP
P_{700}
Photon
Fd
NADP+ reductase
NADP+
+
H^+ H^+
NADPH
+ H^+
© 2001 Sinauer Associates, Inc.
© 2001 Sinauer Associates, Inc.

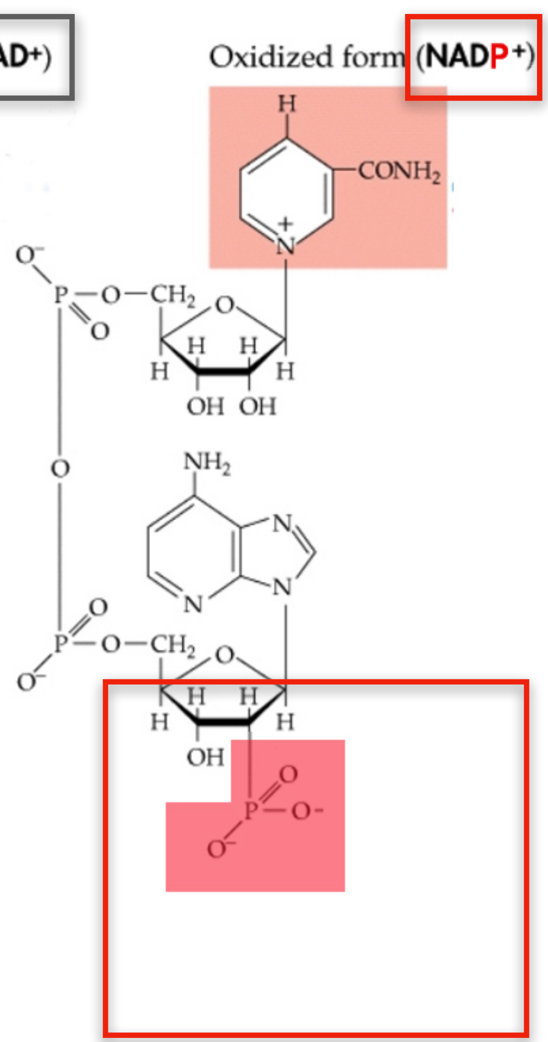

Oxidized form (NAD+)
Oxidized form (NADP+)
$CONH_2$
NH_2
CH_2
OH OH


Photosystem I
Fd
NADP+ reductase
e⁻
P_{700}
NADP+
+
H^+ H^+
NADPH
+ H^+
Photon

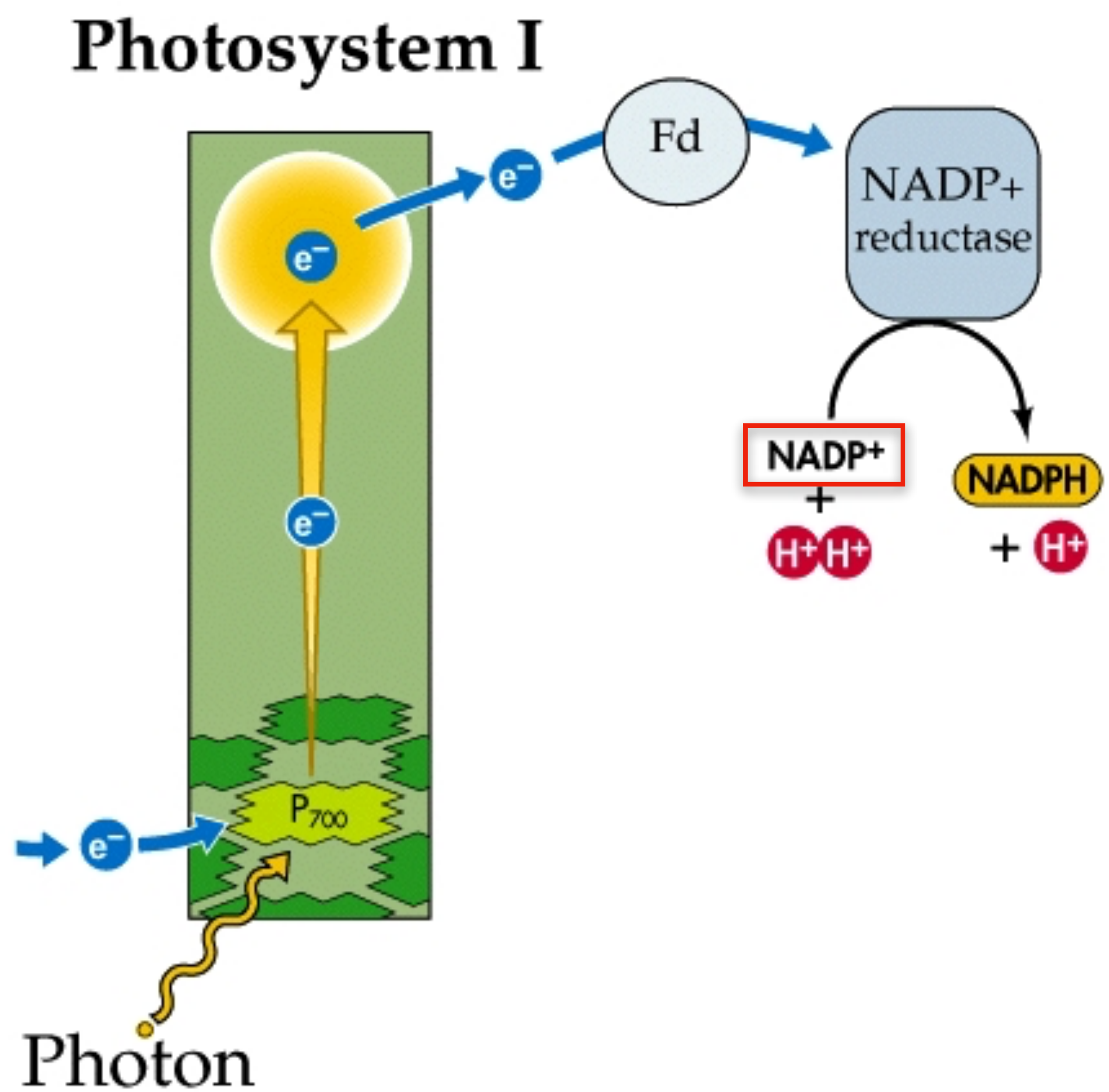


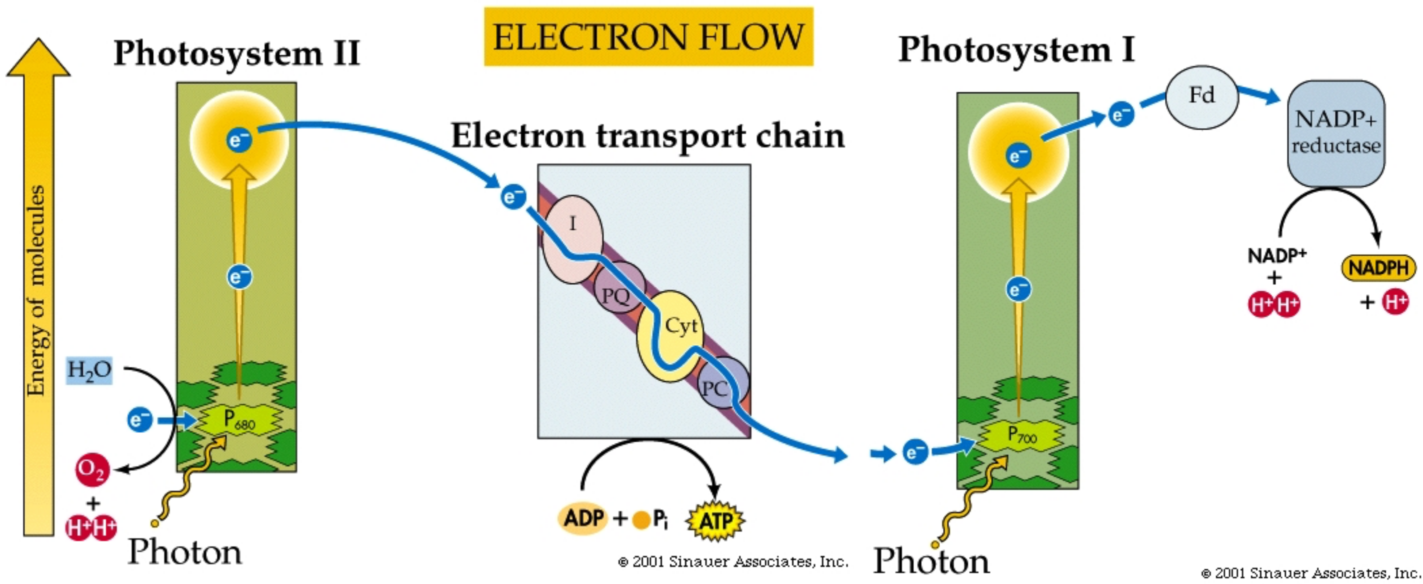


Catabolic

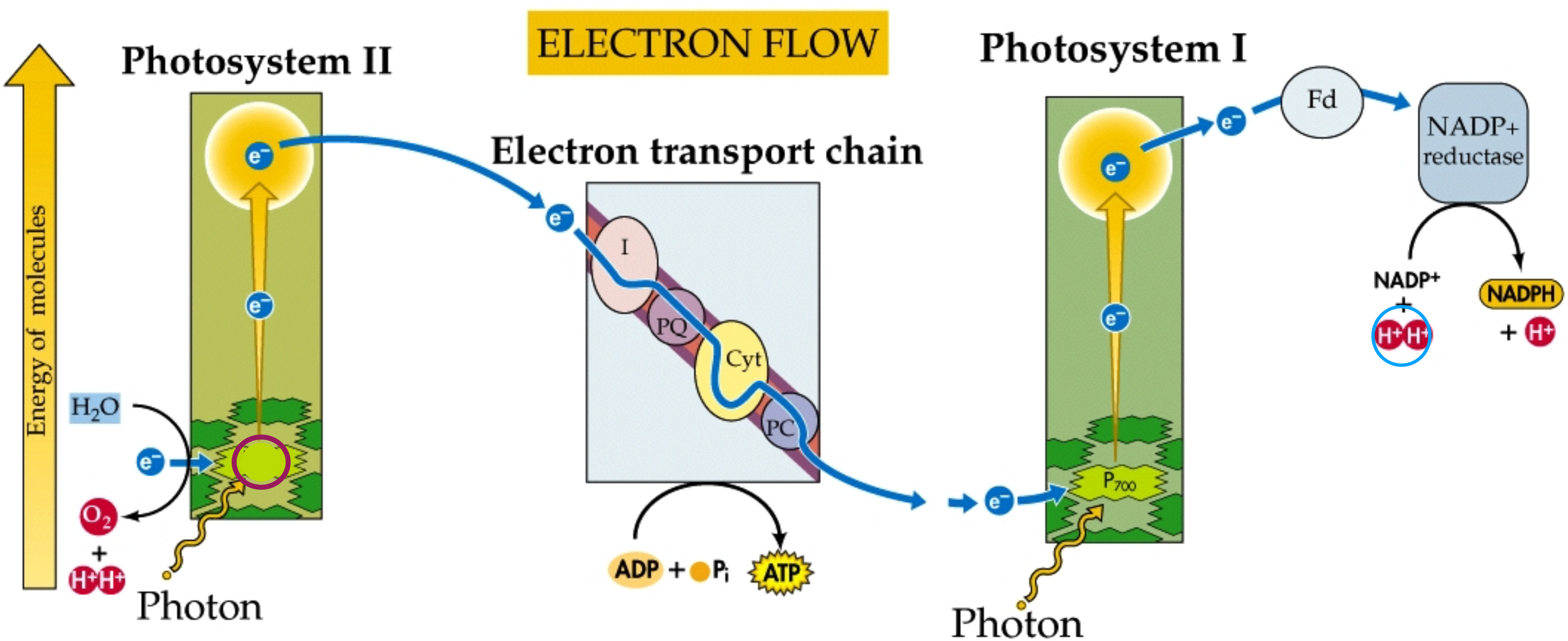


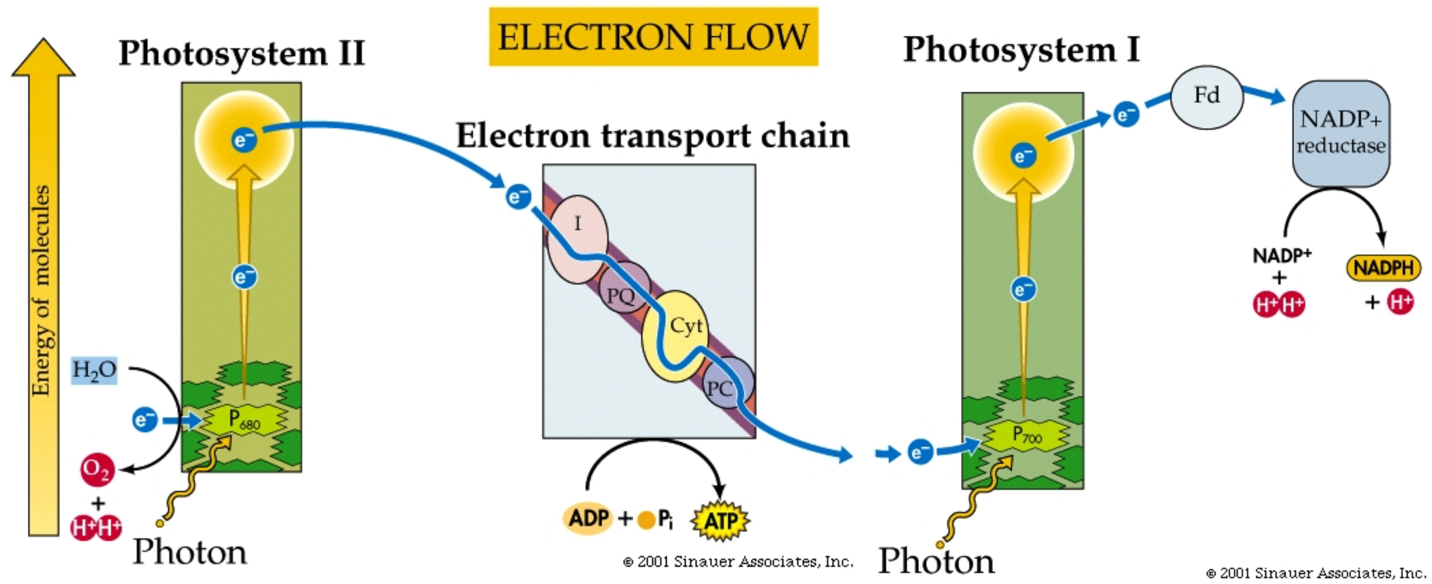
Anabolic



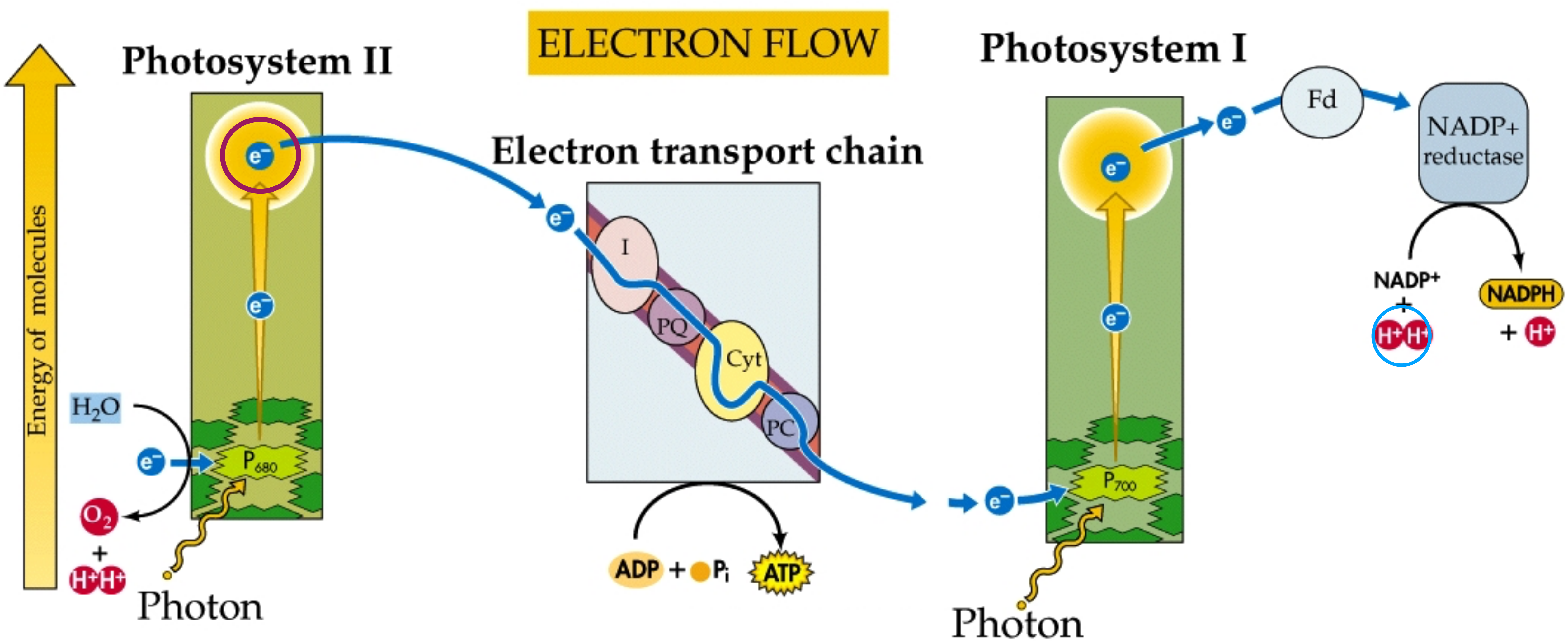


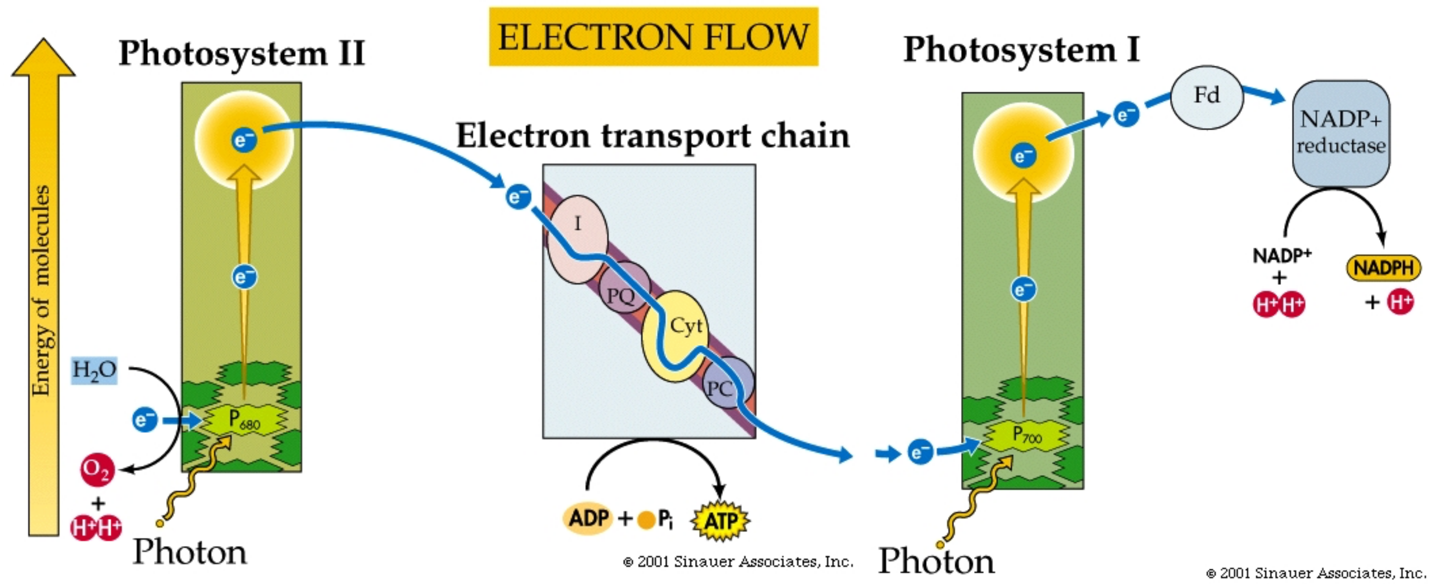
Energy Yield
2 x



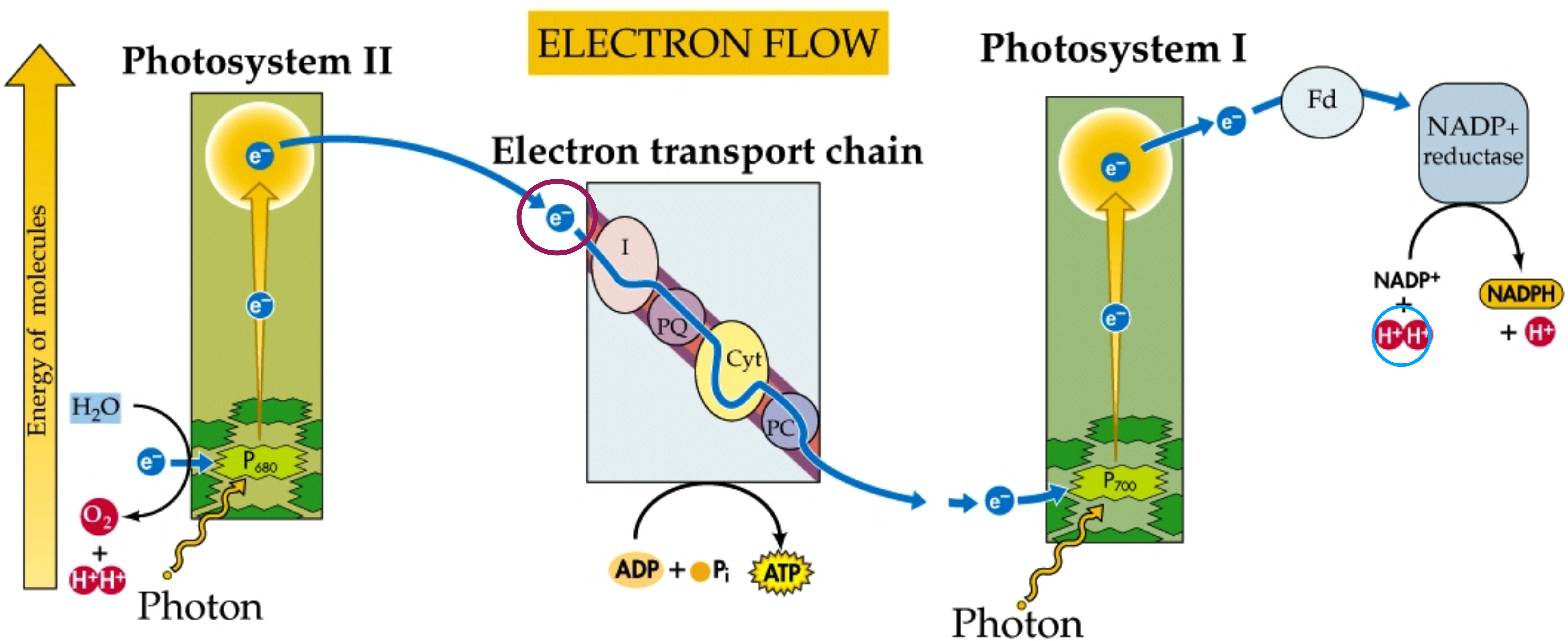


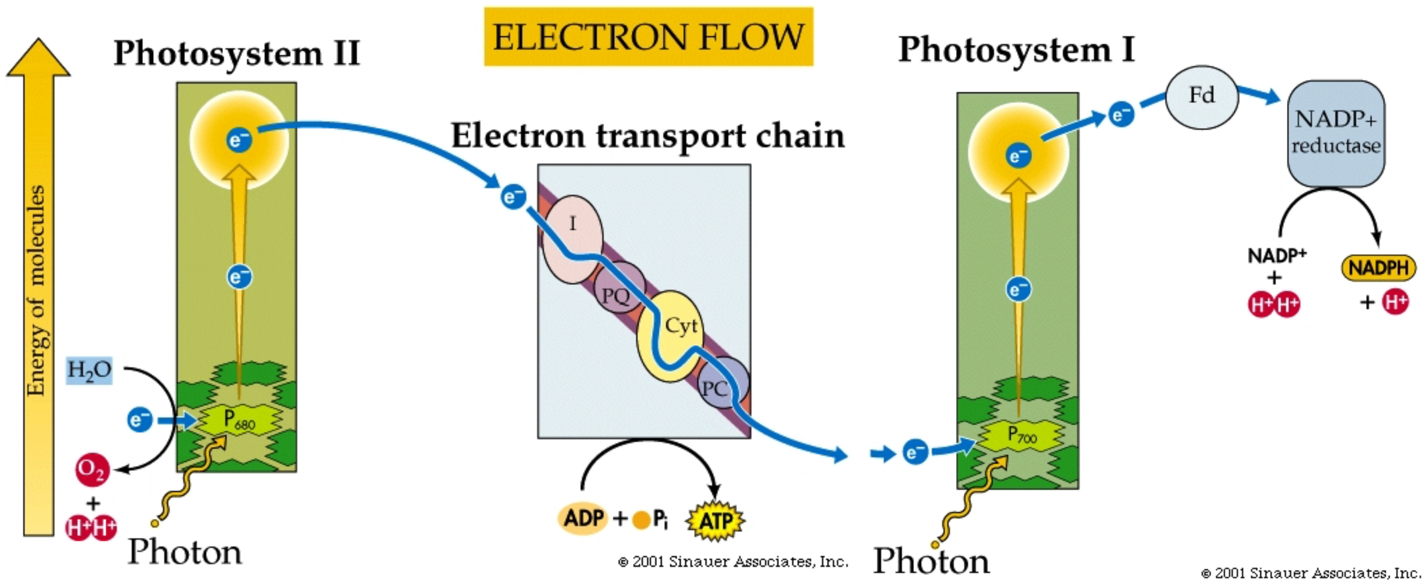
Energy Yield
2 x



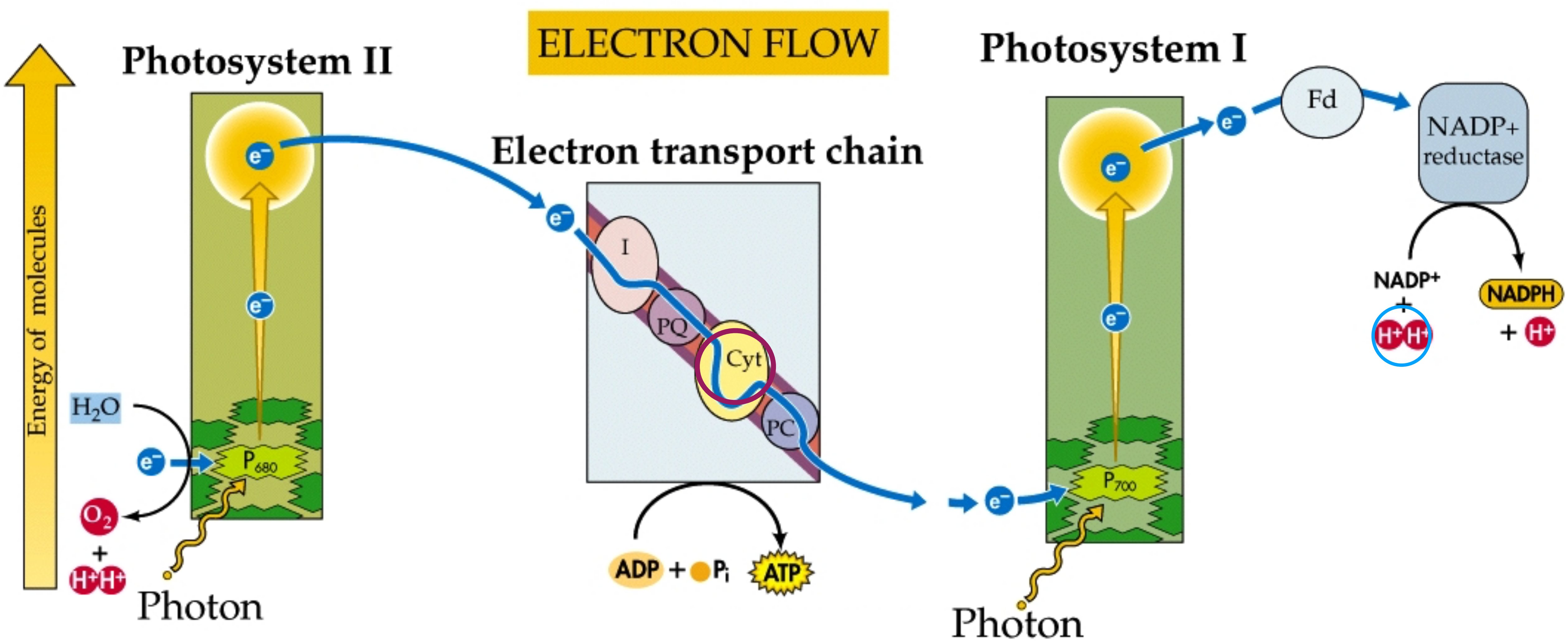


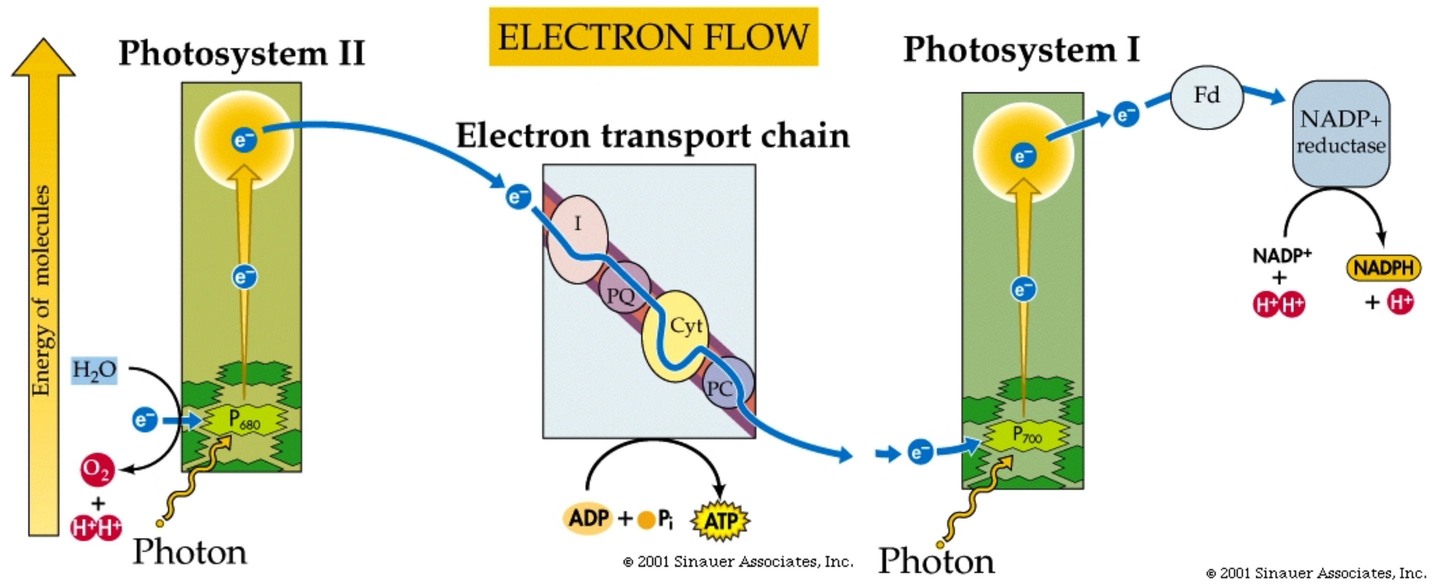
Energy Yield
2 x



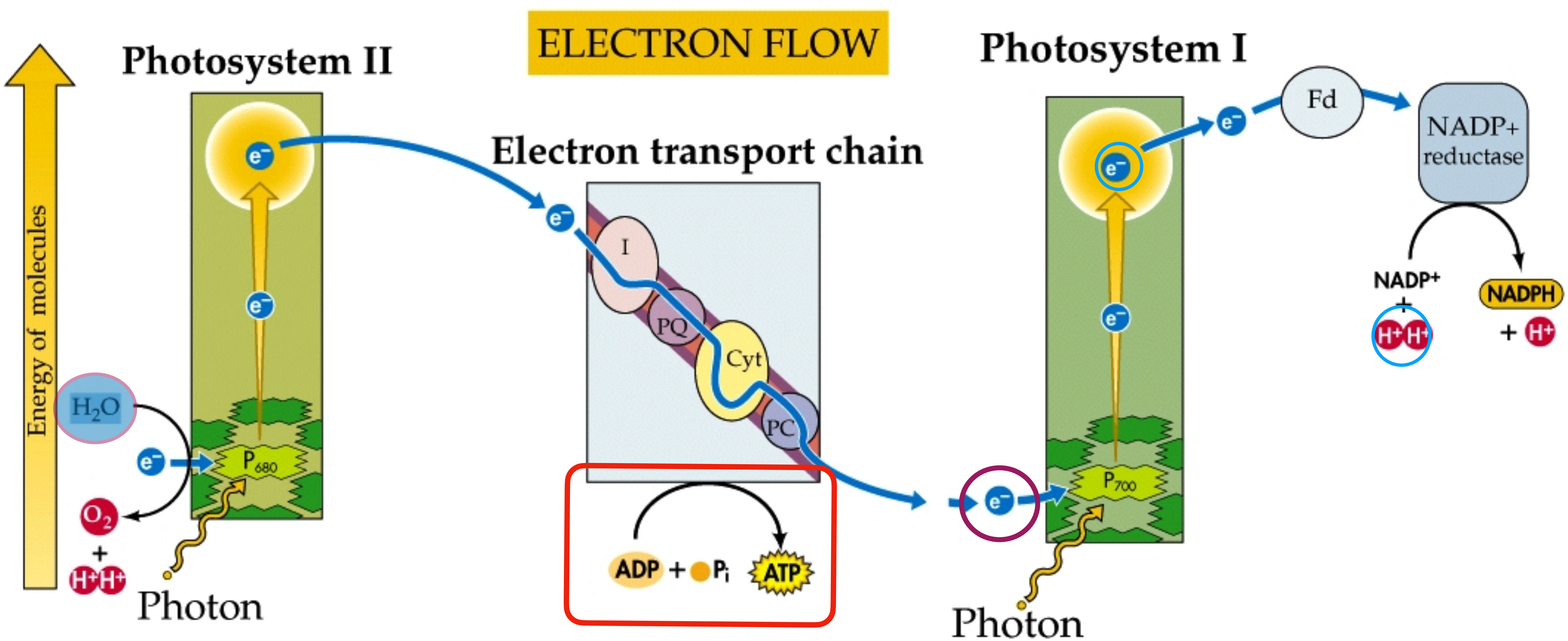


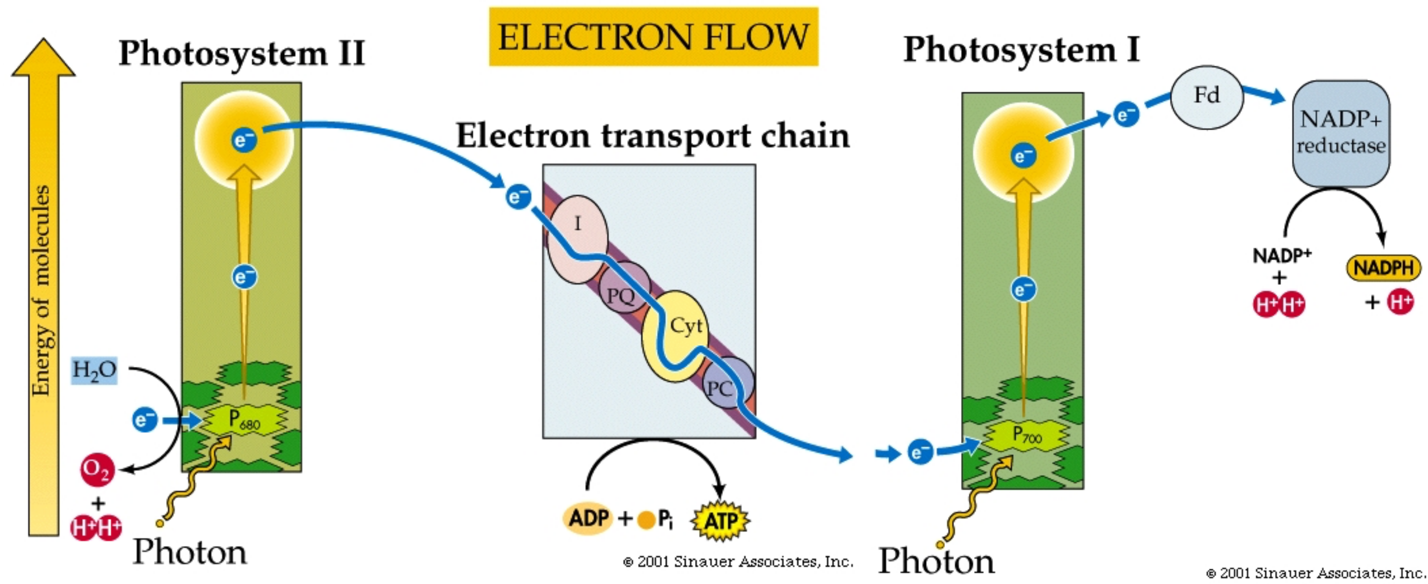
Energy Yield
2 x



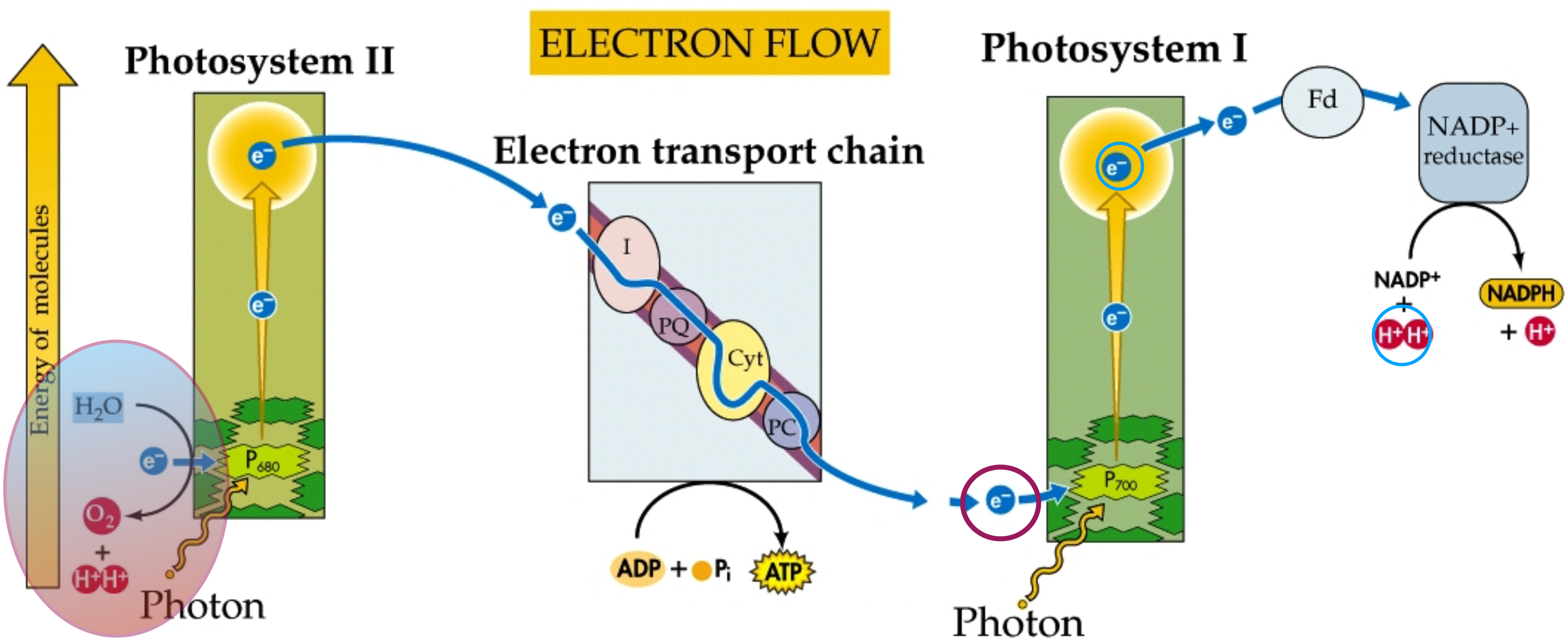


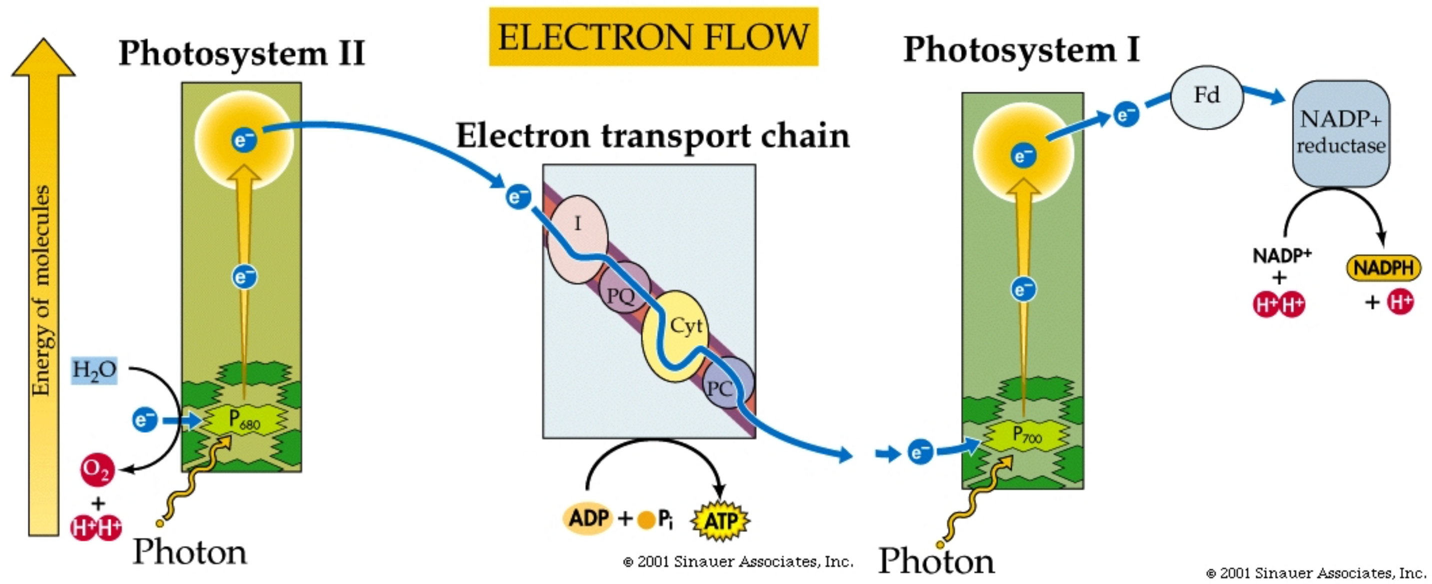
Energy Yield
2 x



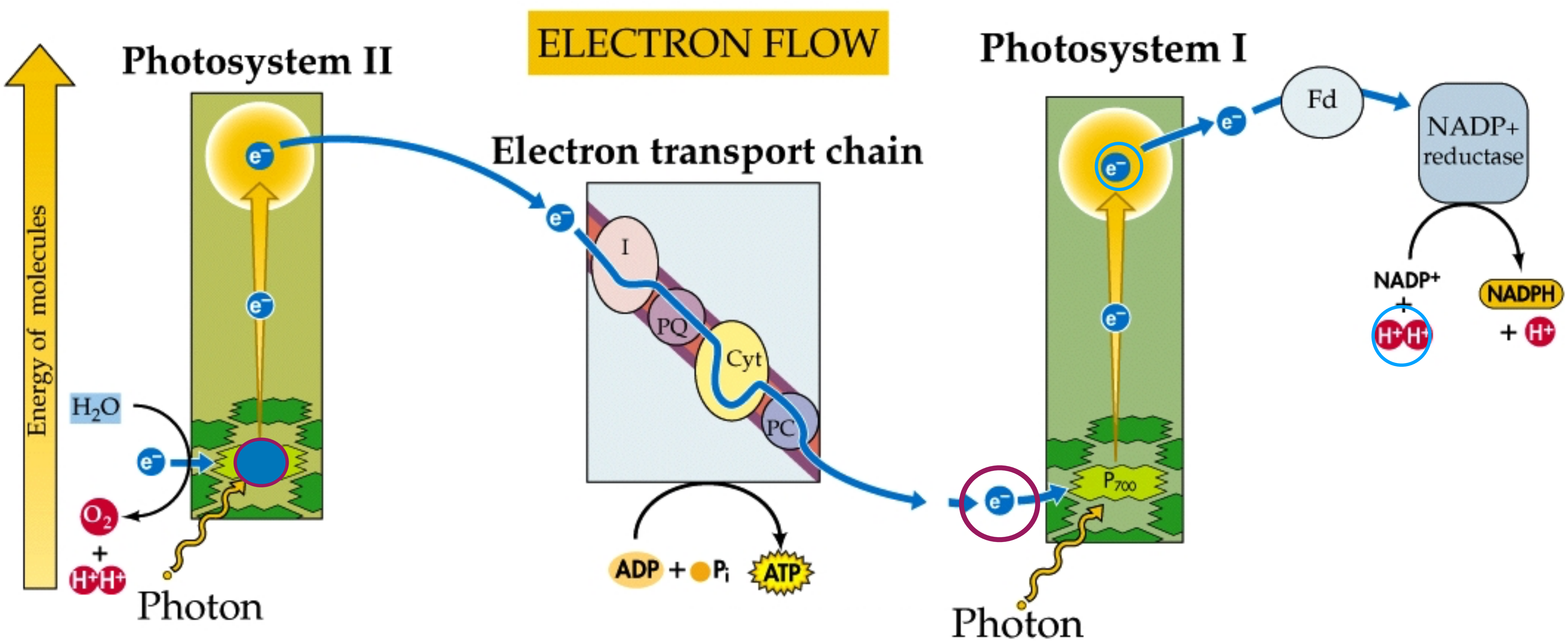


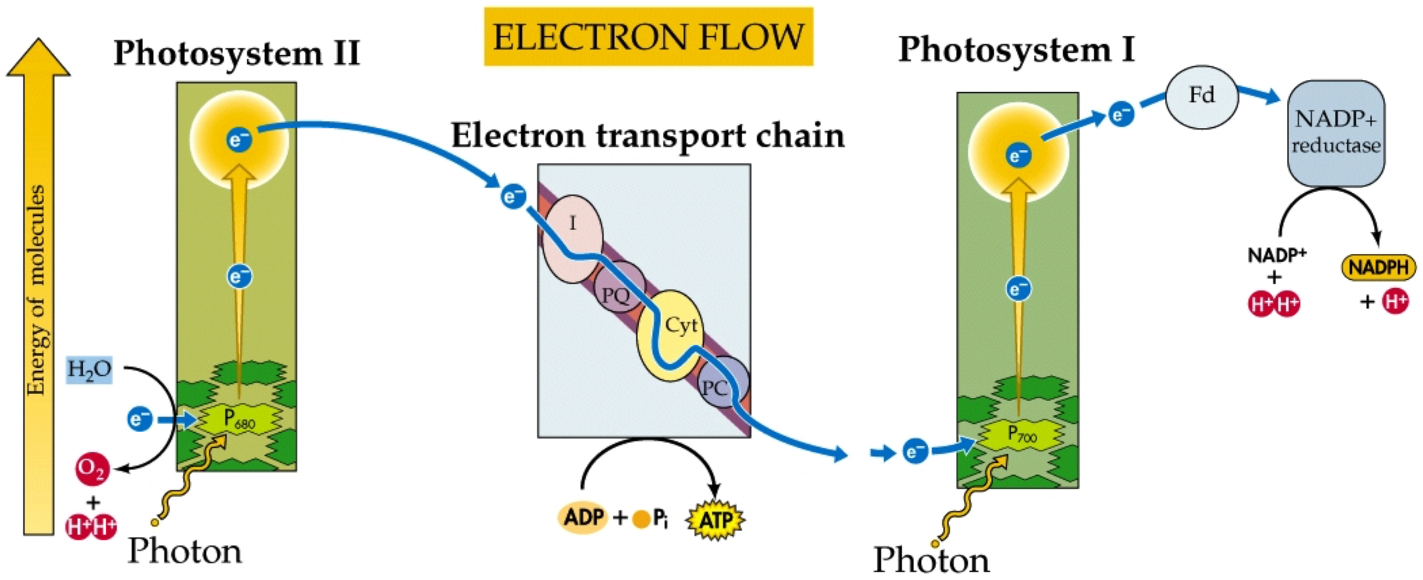
Energy Yield
2 x



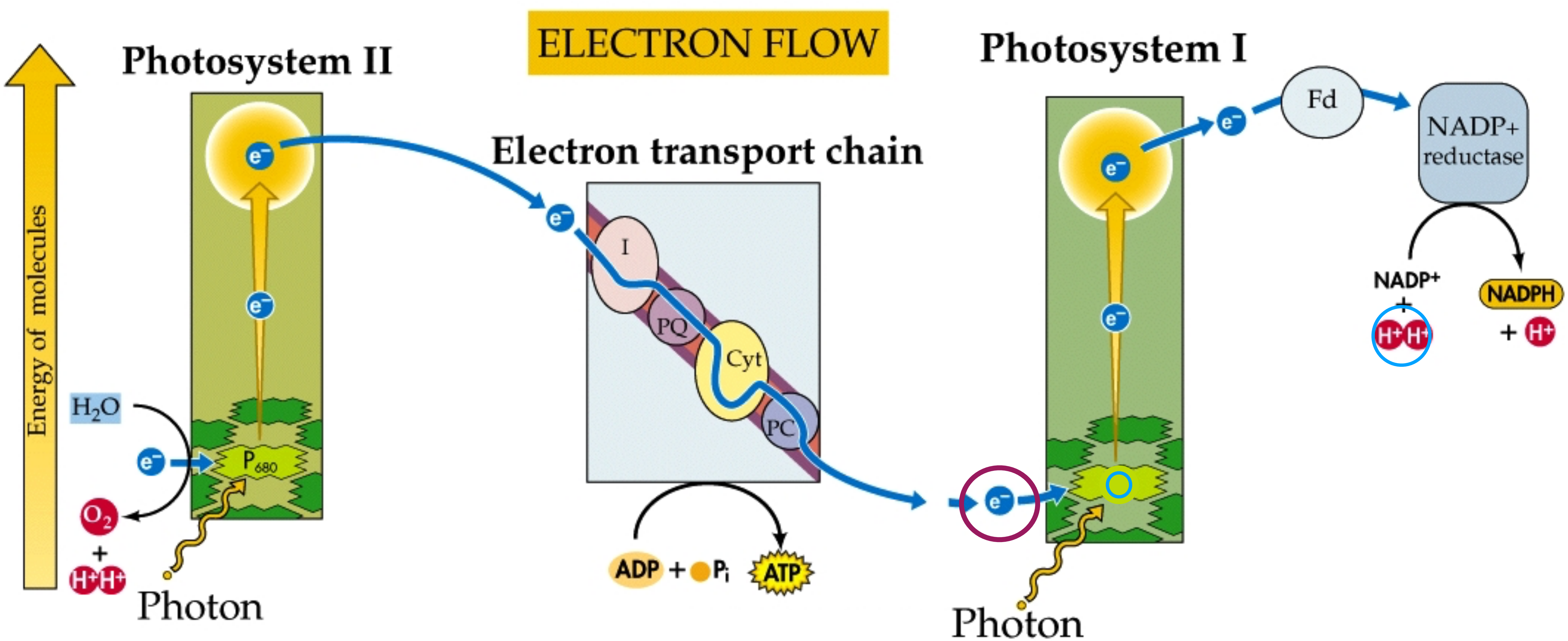


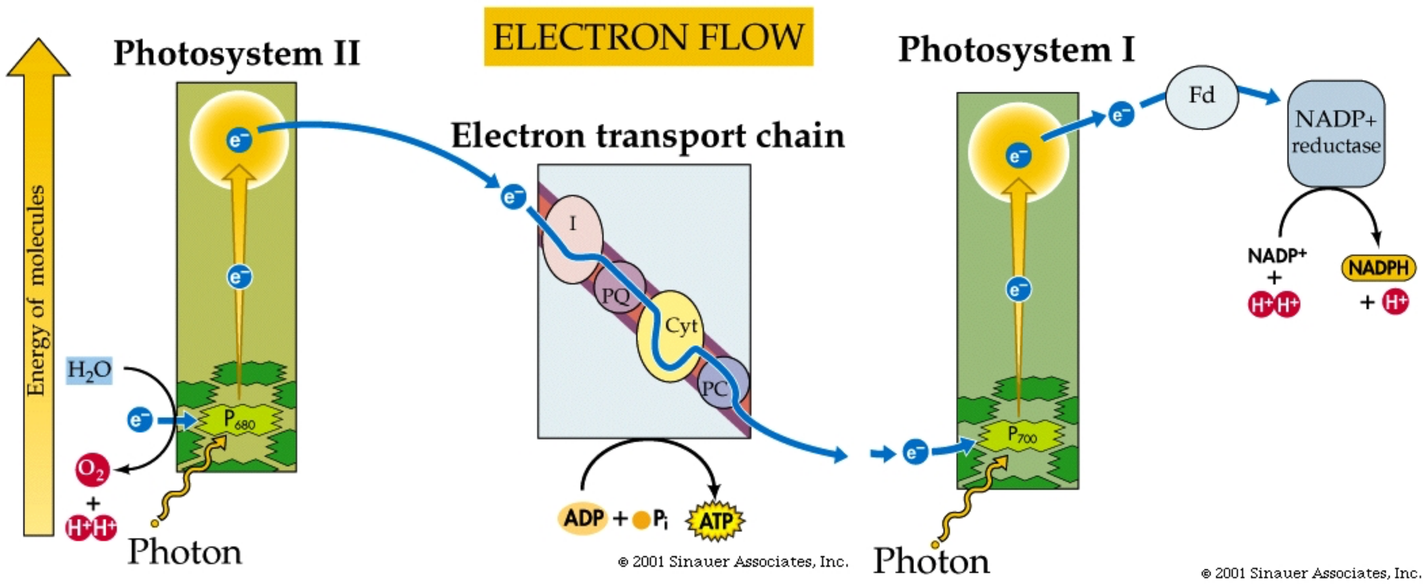
Energy Yield
2 x



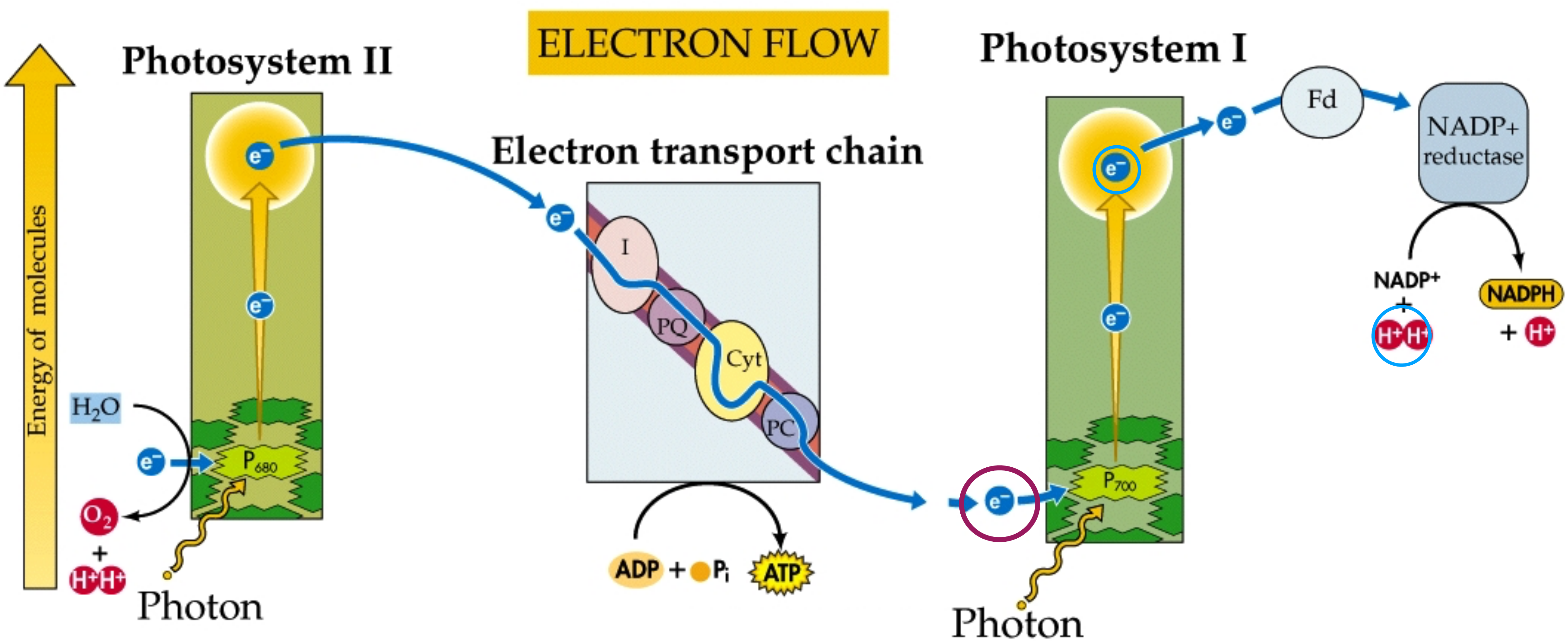


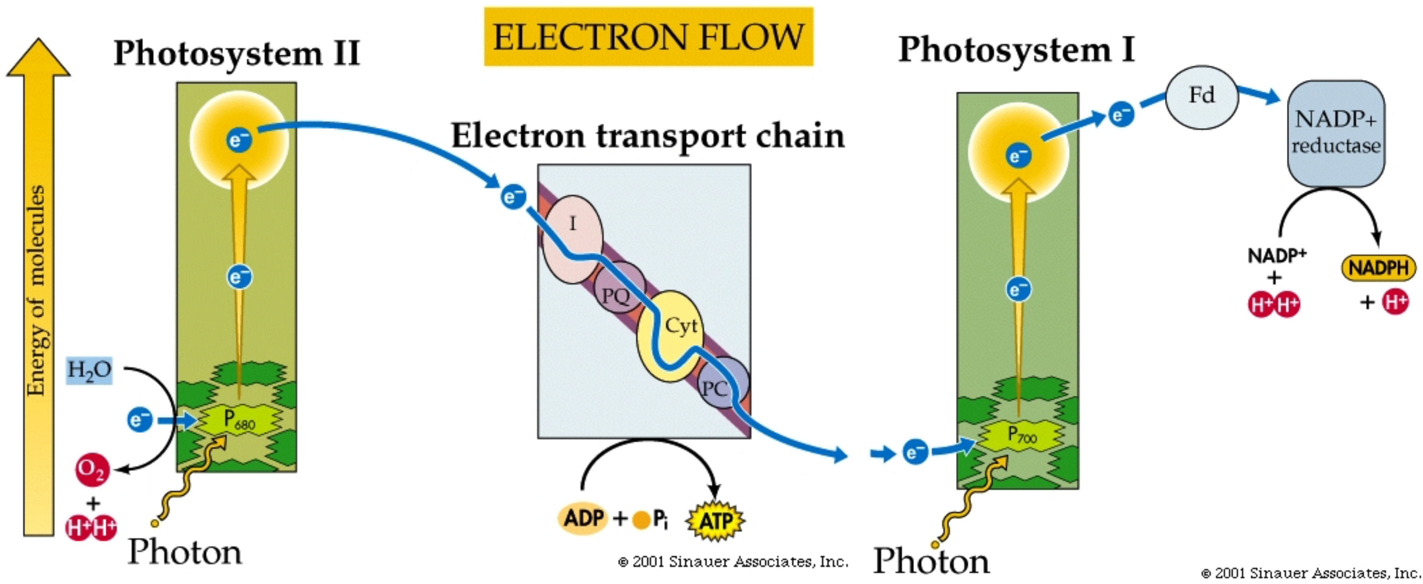
Energy Yield
2 x



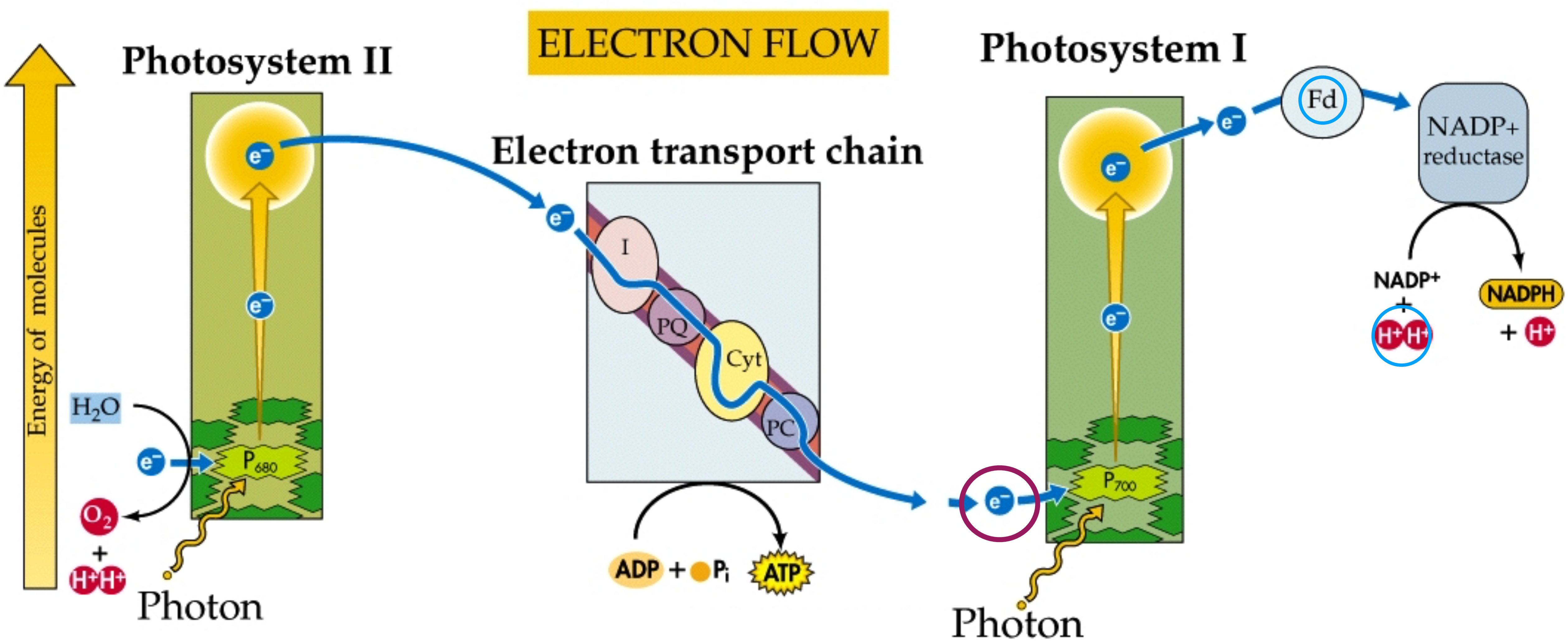


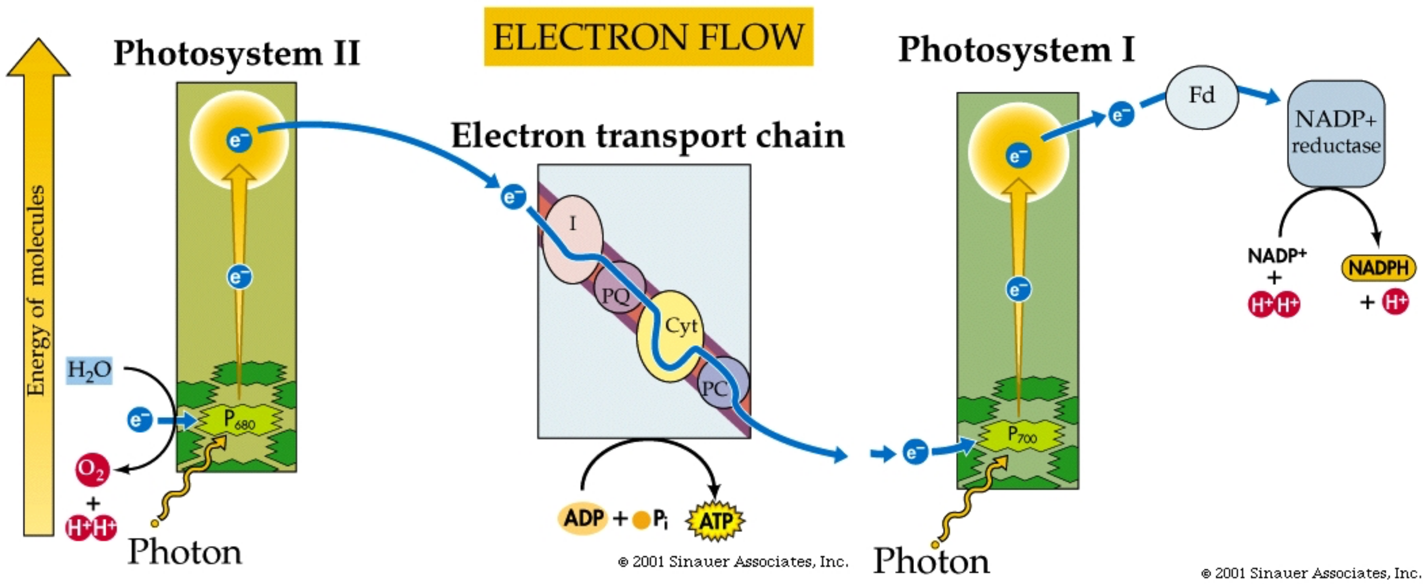
Energy Yield
2 x



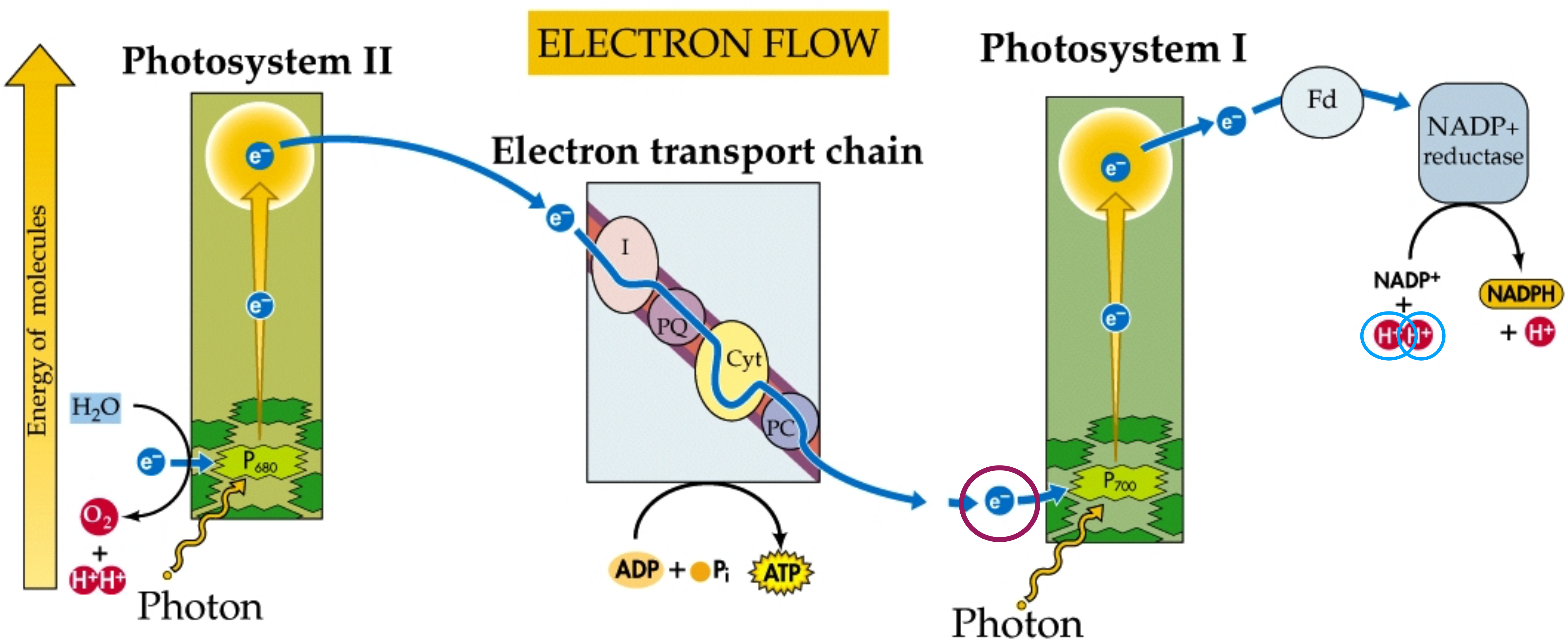


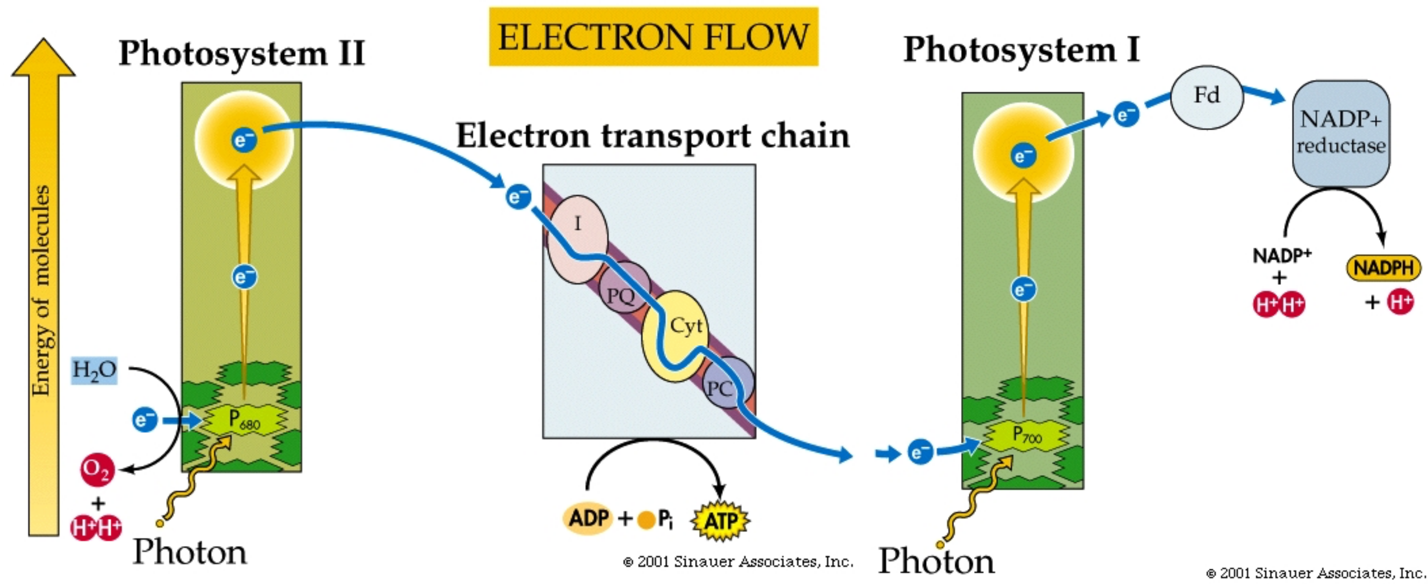
Energy Yield
2 x



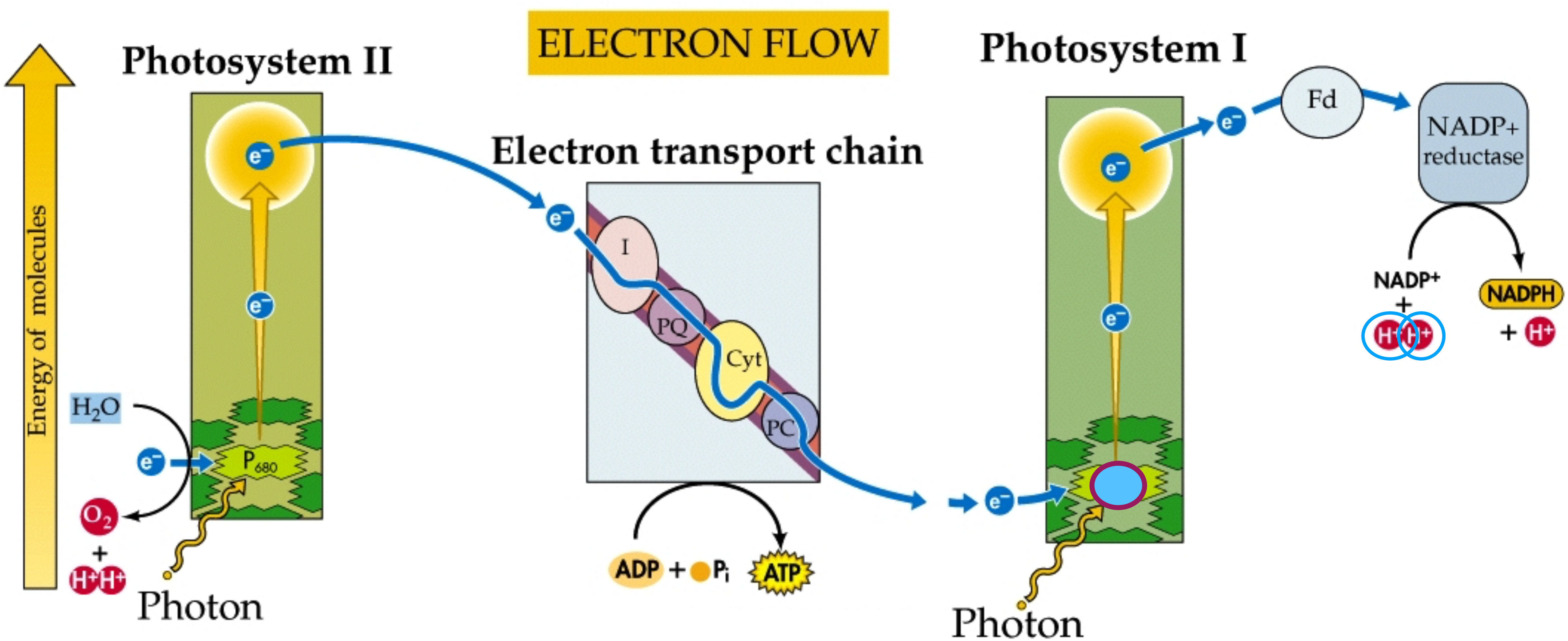


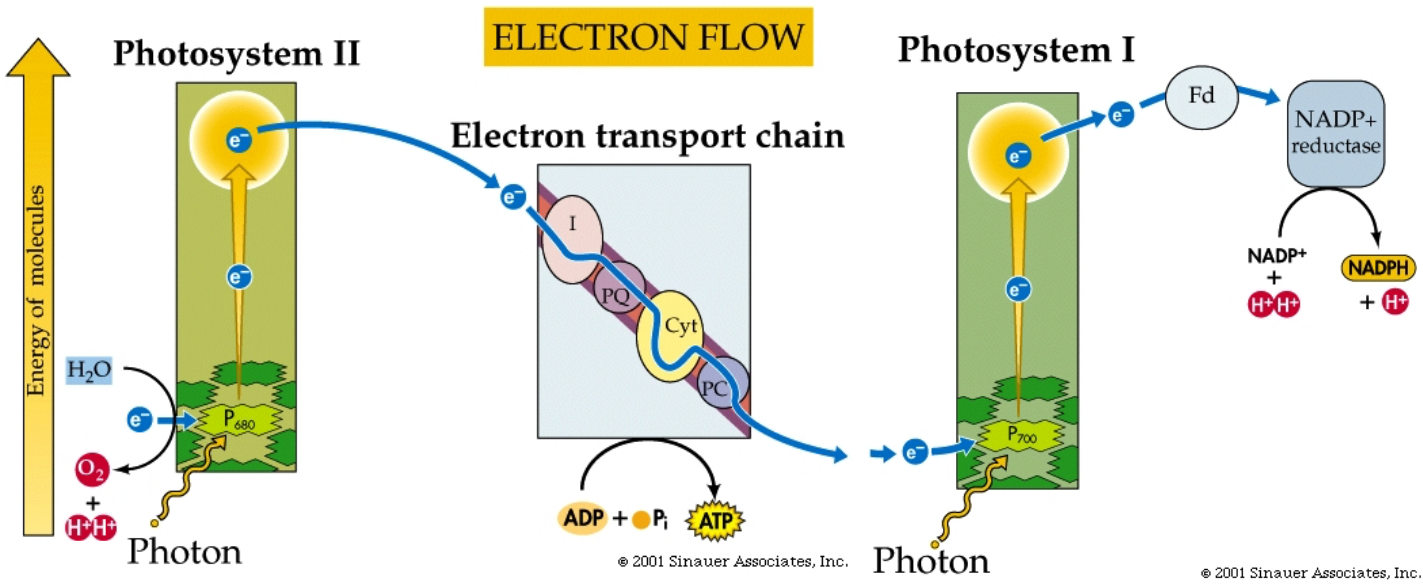
Energy Yield
2 x



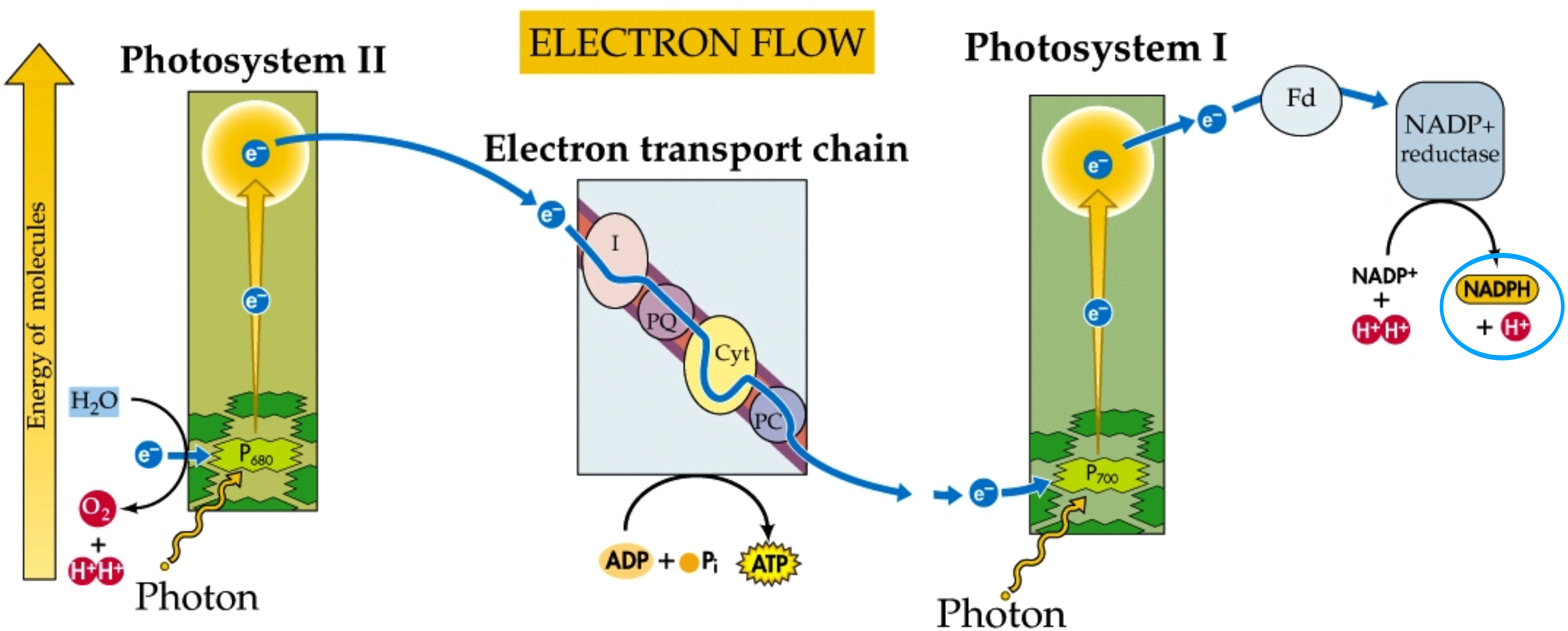


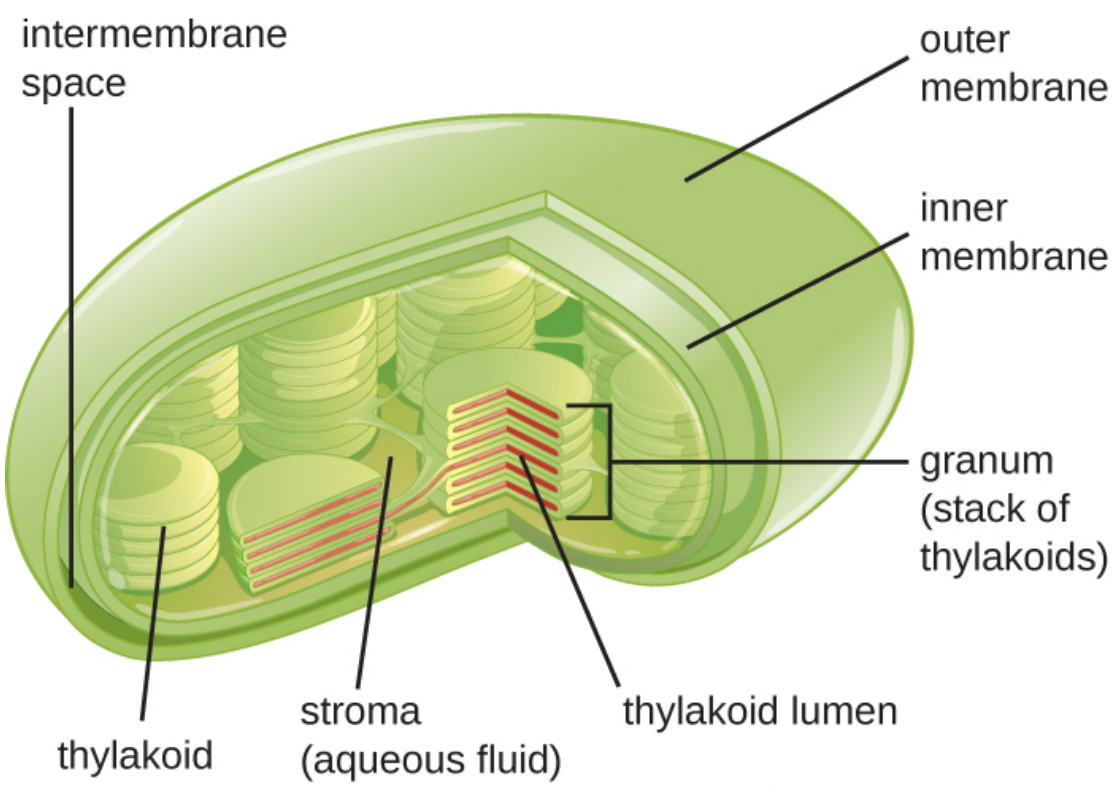
Energy Yield
2 x

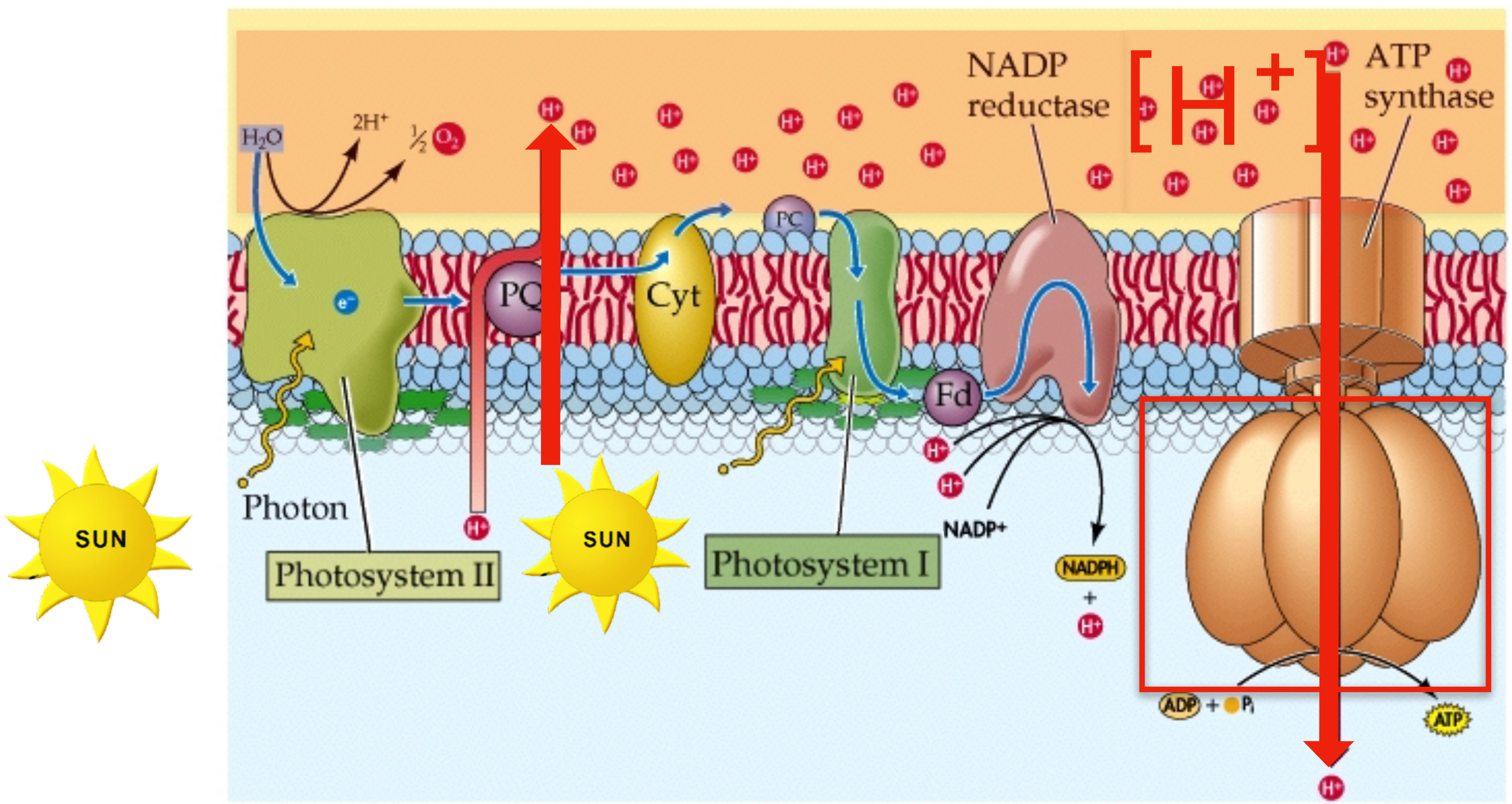




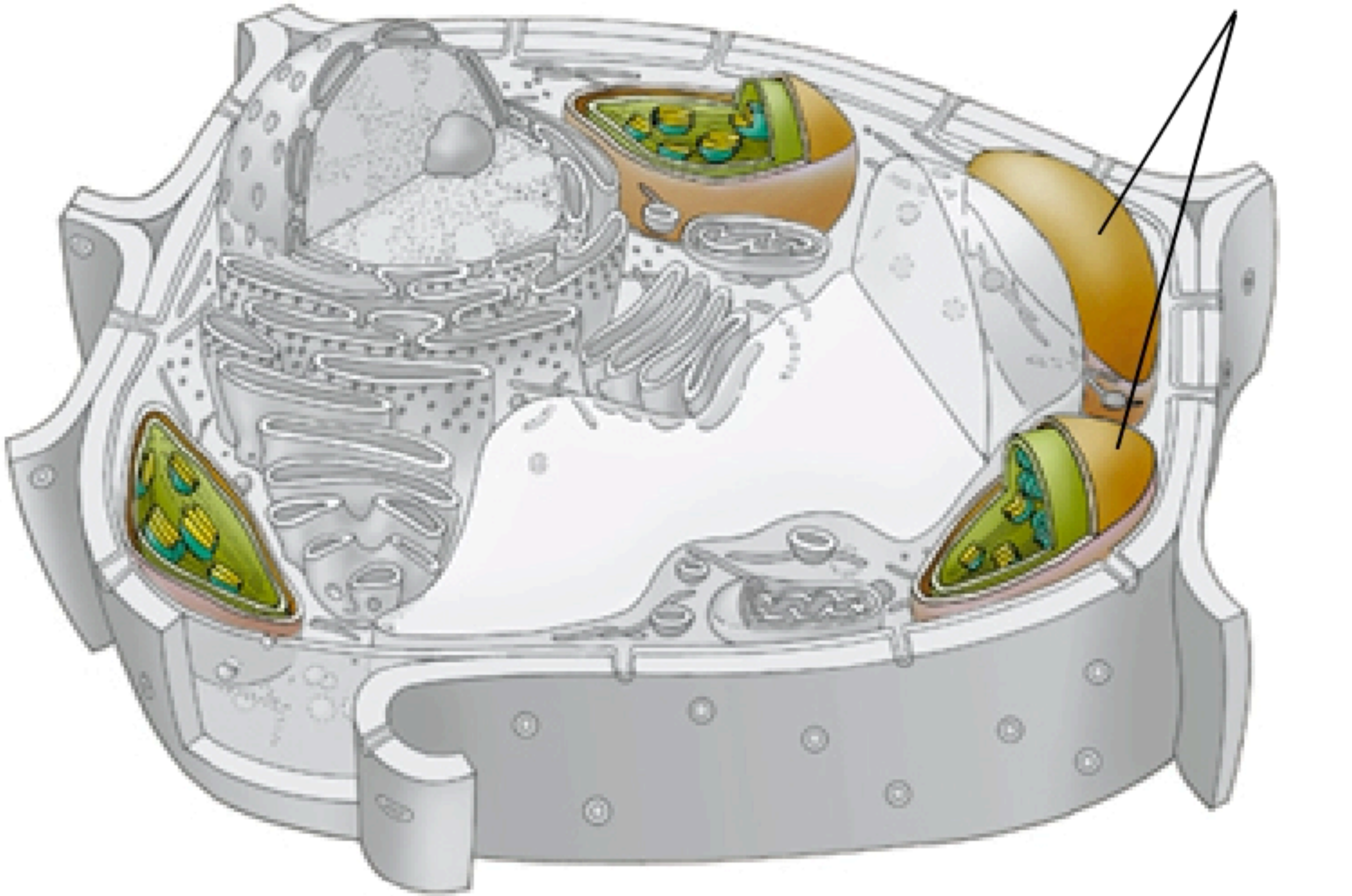
Energy Yield
2 x

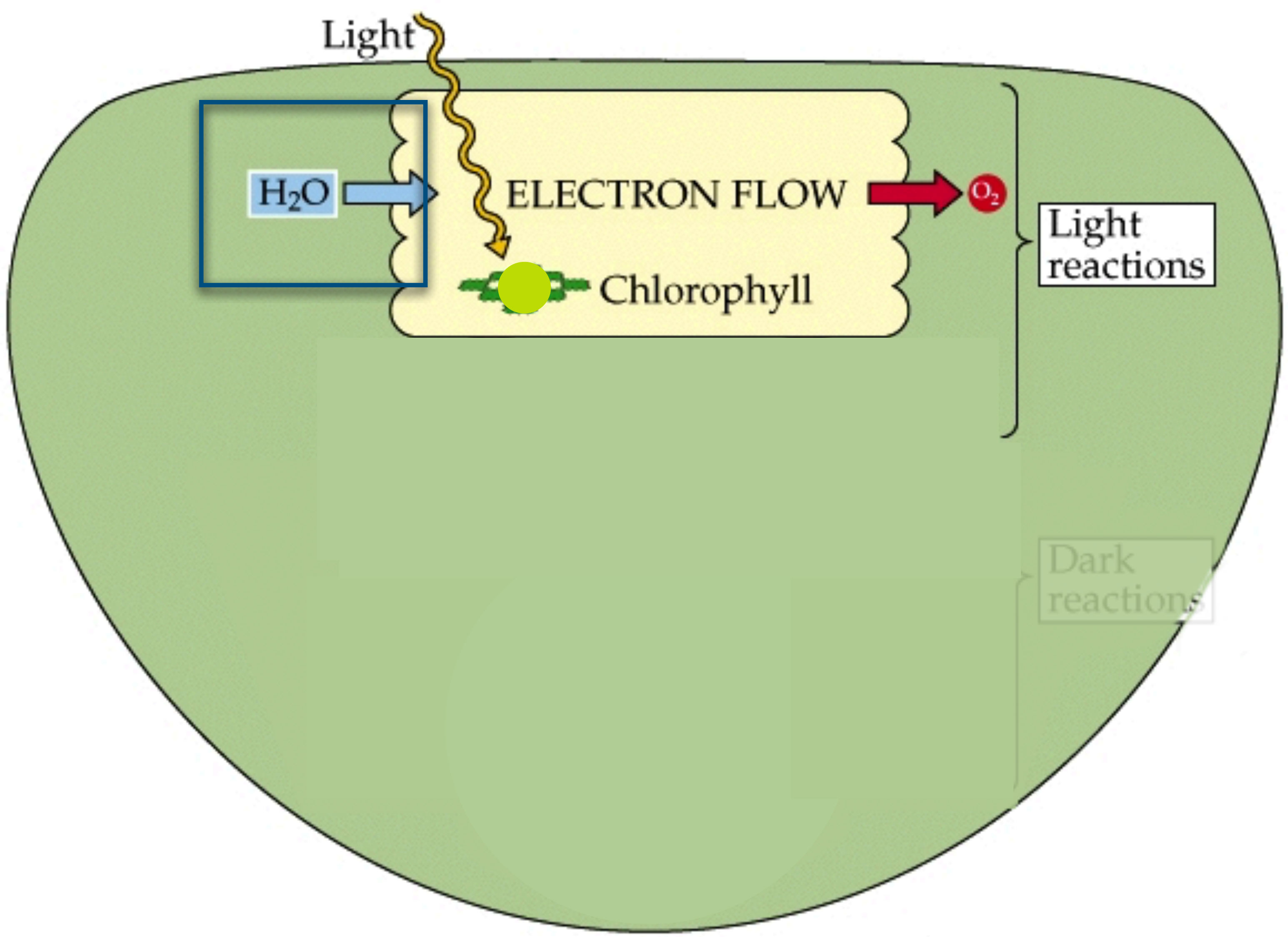


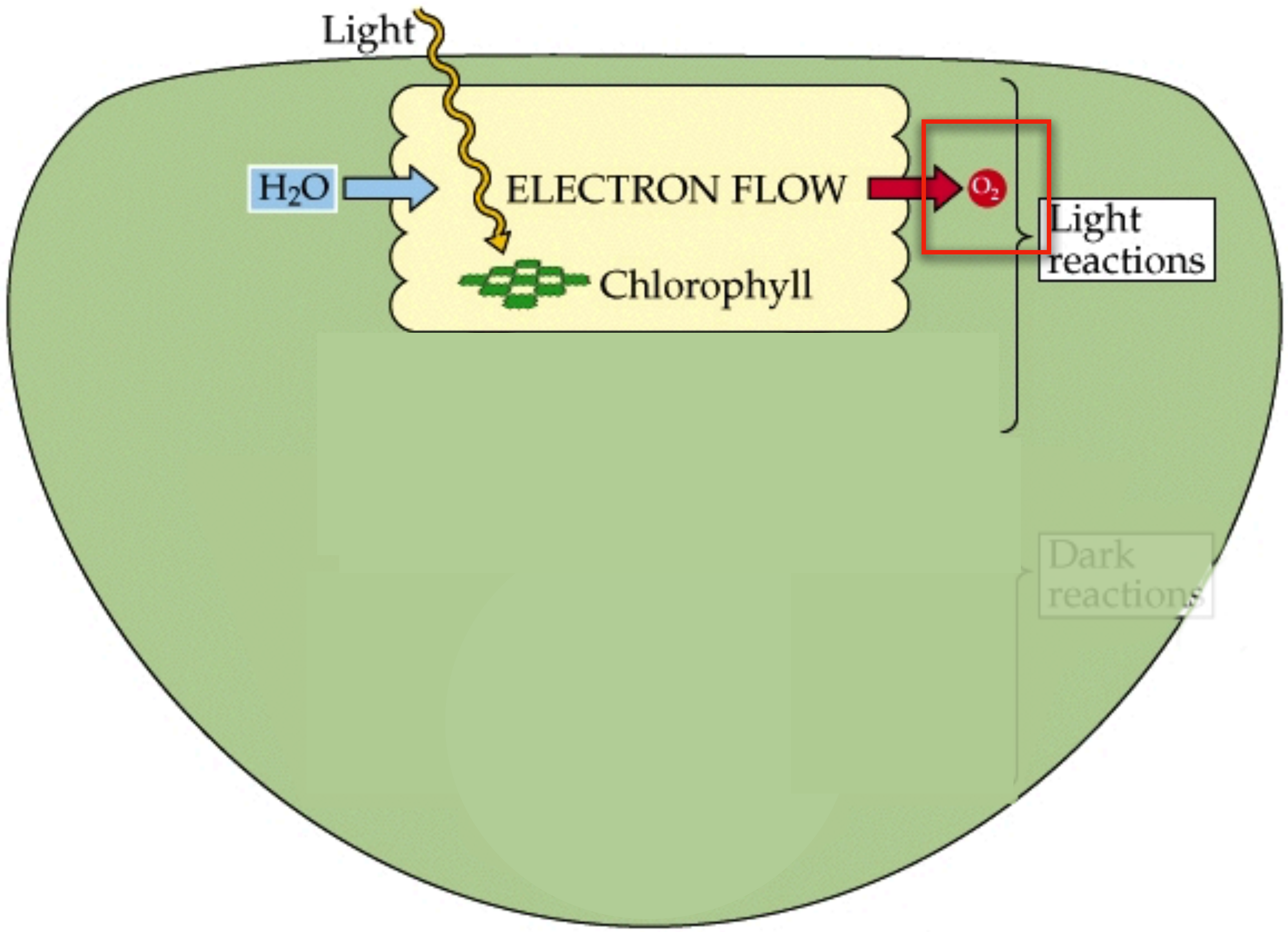

intermembrane space
outer membrane
inner membrane
granum (stack of thylakoids)
thylakoid
stroma (aqueous fluid)
thylakoid lumen

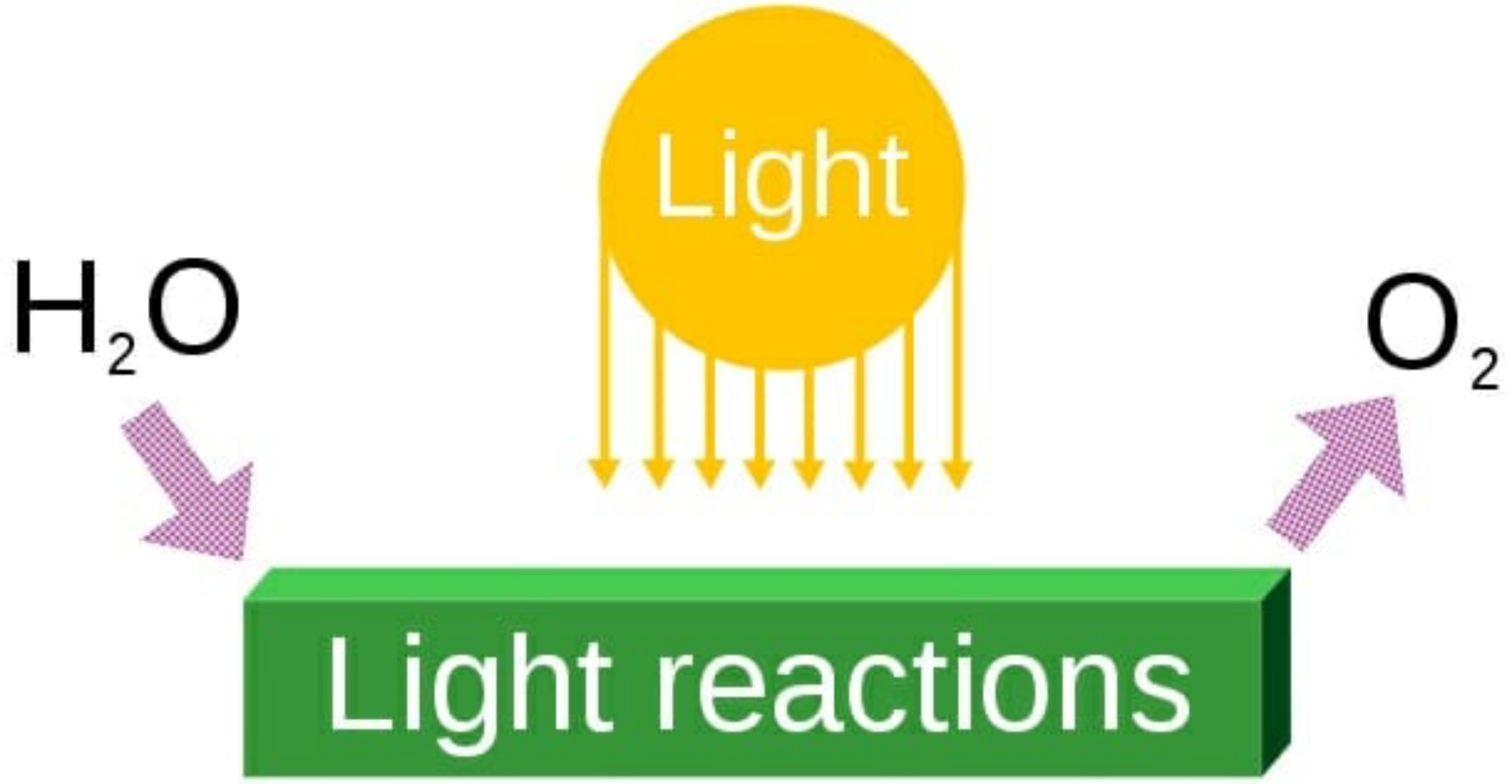

H2O
2H+
½ O2
NADP reductase
[H+]
ATP synthase
PQ
Cyt
PC
e-
Fd
Photon
SUN
SUN
Photosystem II
Photosystem I
NADP+
NADPH
+
ADP + Pi
ATP

A Plant Cell



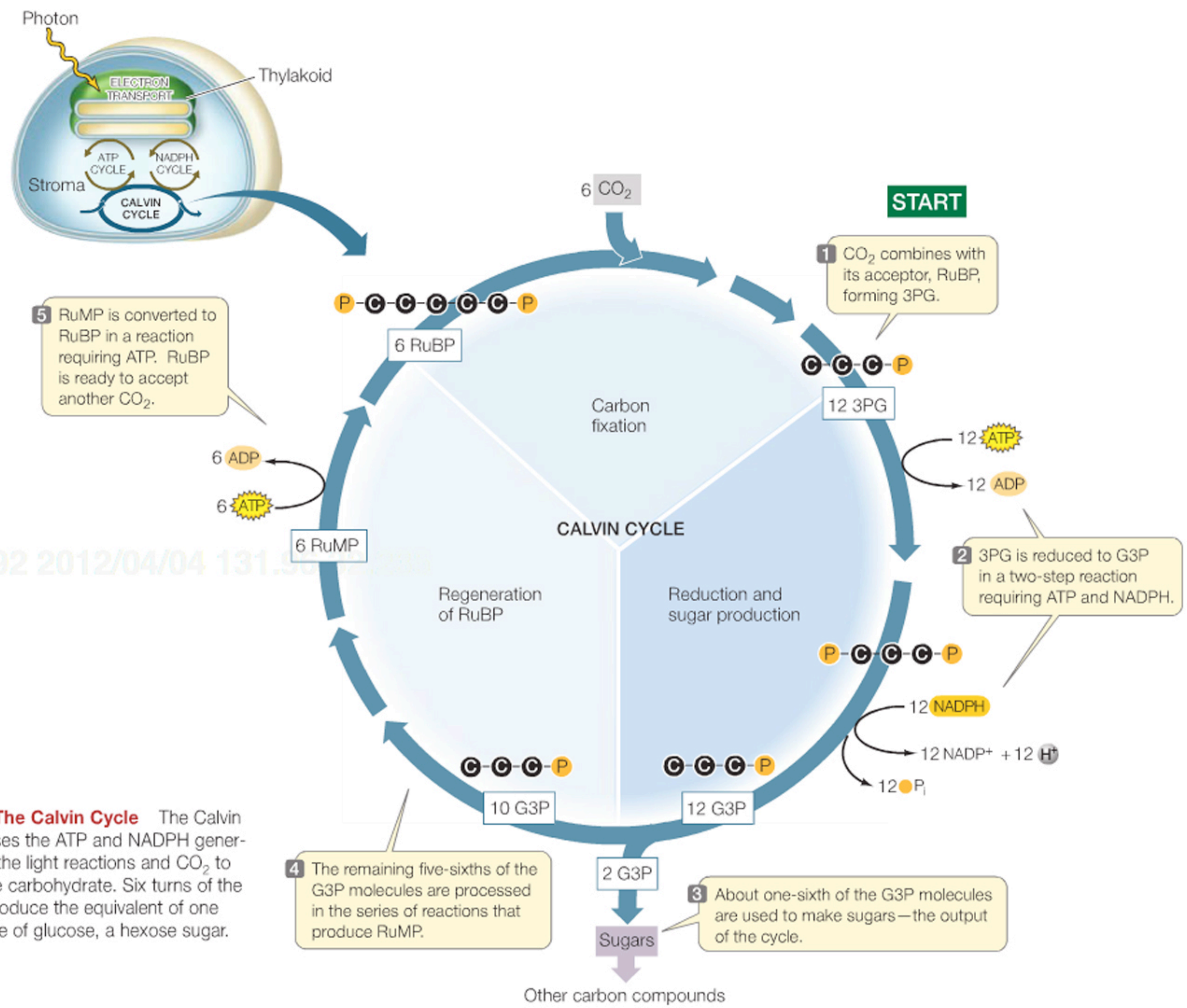

Light
H_2O
ELECTRON FLOW
O_2
Chlorophyll
Light reactions
Dark reactions


Light
H_2O
ELECTRON FLOW
O_2
Chlorophyll
Light
reactions
Dark
reactions

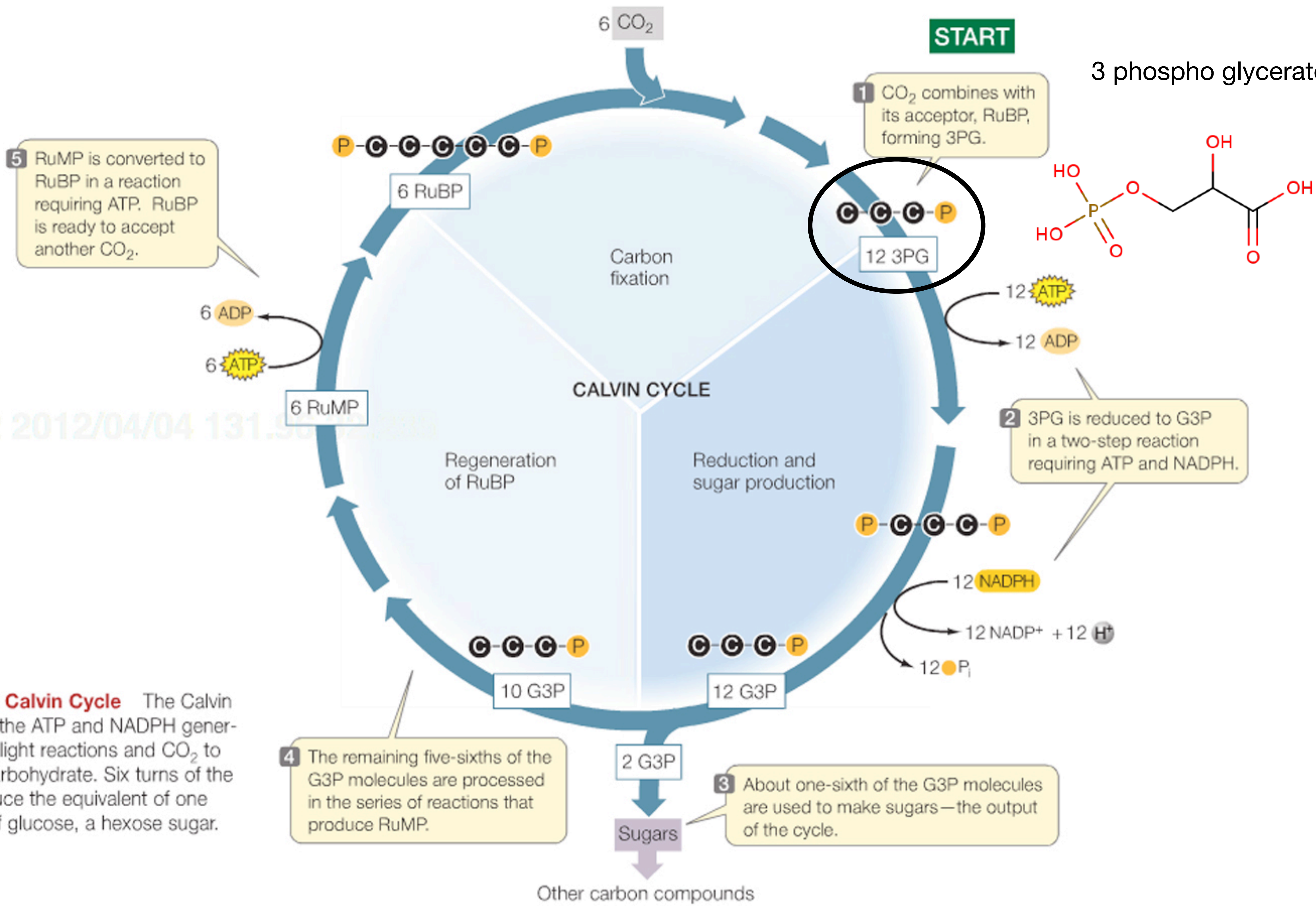


The **Dark Reaction....** better know as the **Calvin-Benson cycle,** which is composed of three processes to reduce CO_2 to carbohydrate (the last part of the photosynthetic equation referenced earlier).

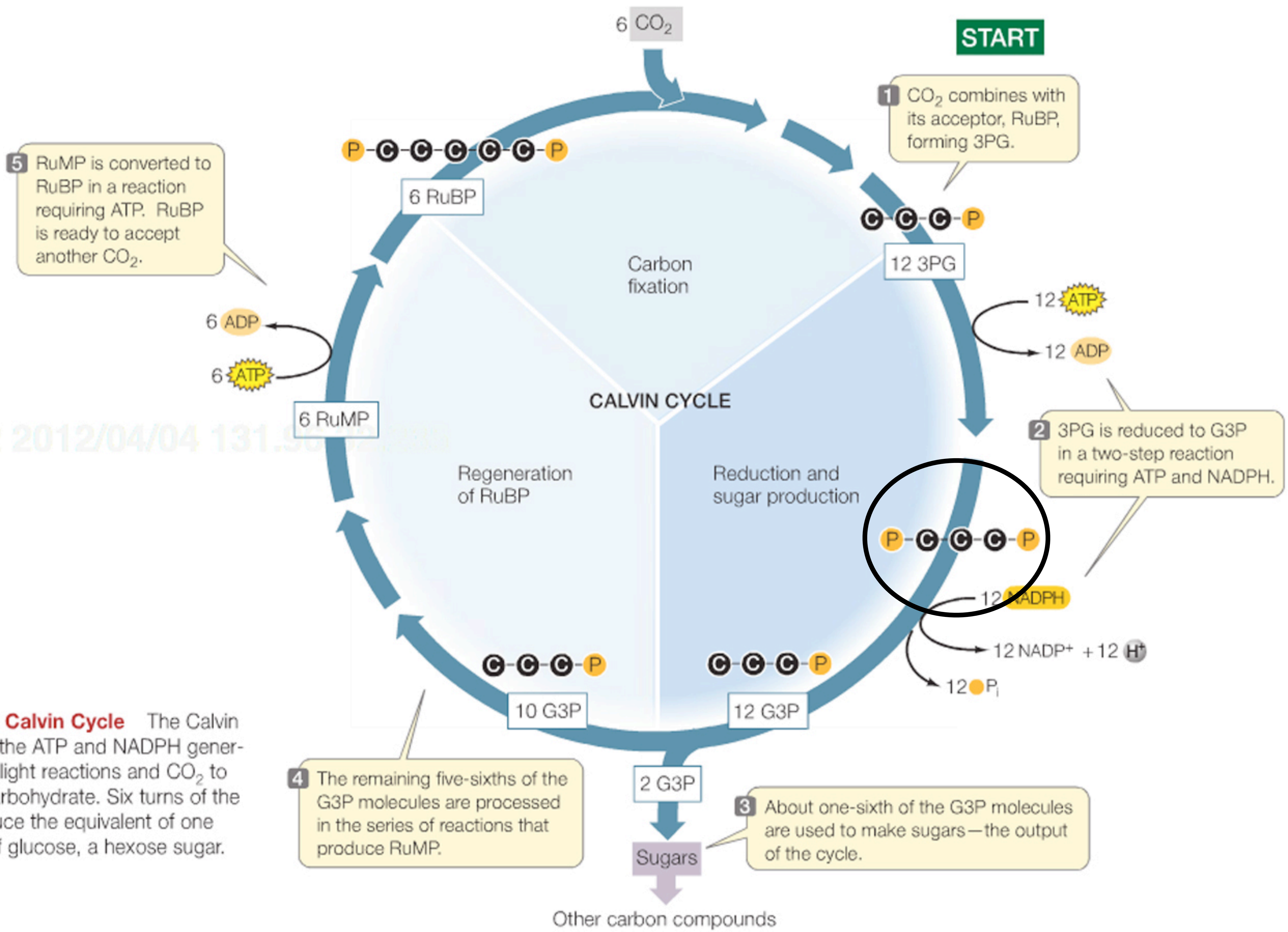
The **Dark Reaction....** better know as the **Calvin-Benson cycle,** which is composed of three processes to reduce CO_2 to carbohydrate (the last part of the photosynthetic equation referenced earlier).



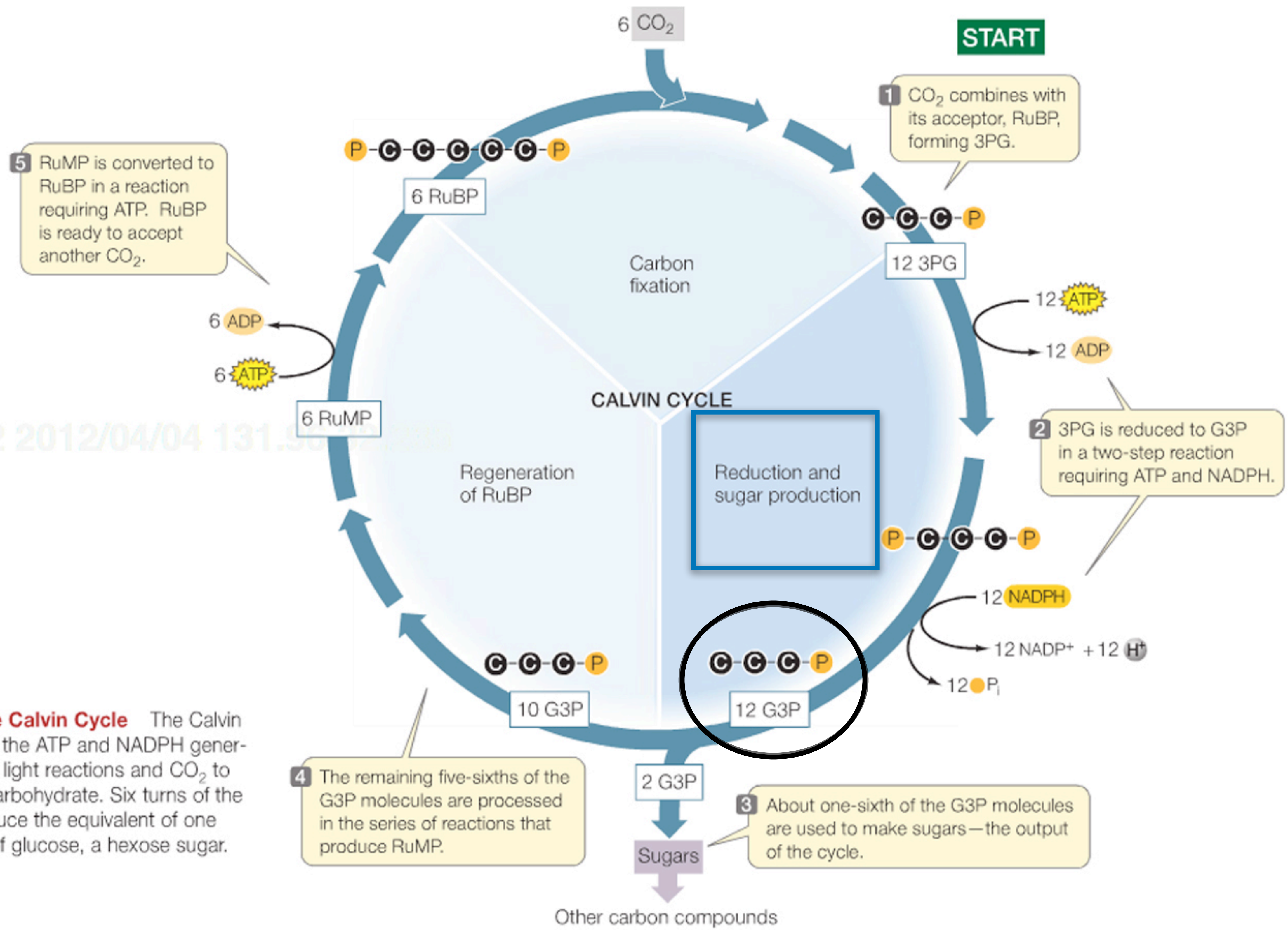
10.15 The Calvin Cycle The Calvin cycle uses the ATP and NADPH generated in the light reactions and CO_2 to produce carbohydrate. Six turns of the cycle produce the equivalent of one molecule of glucose, a hexose sugar.



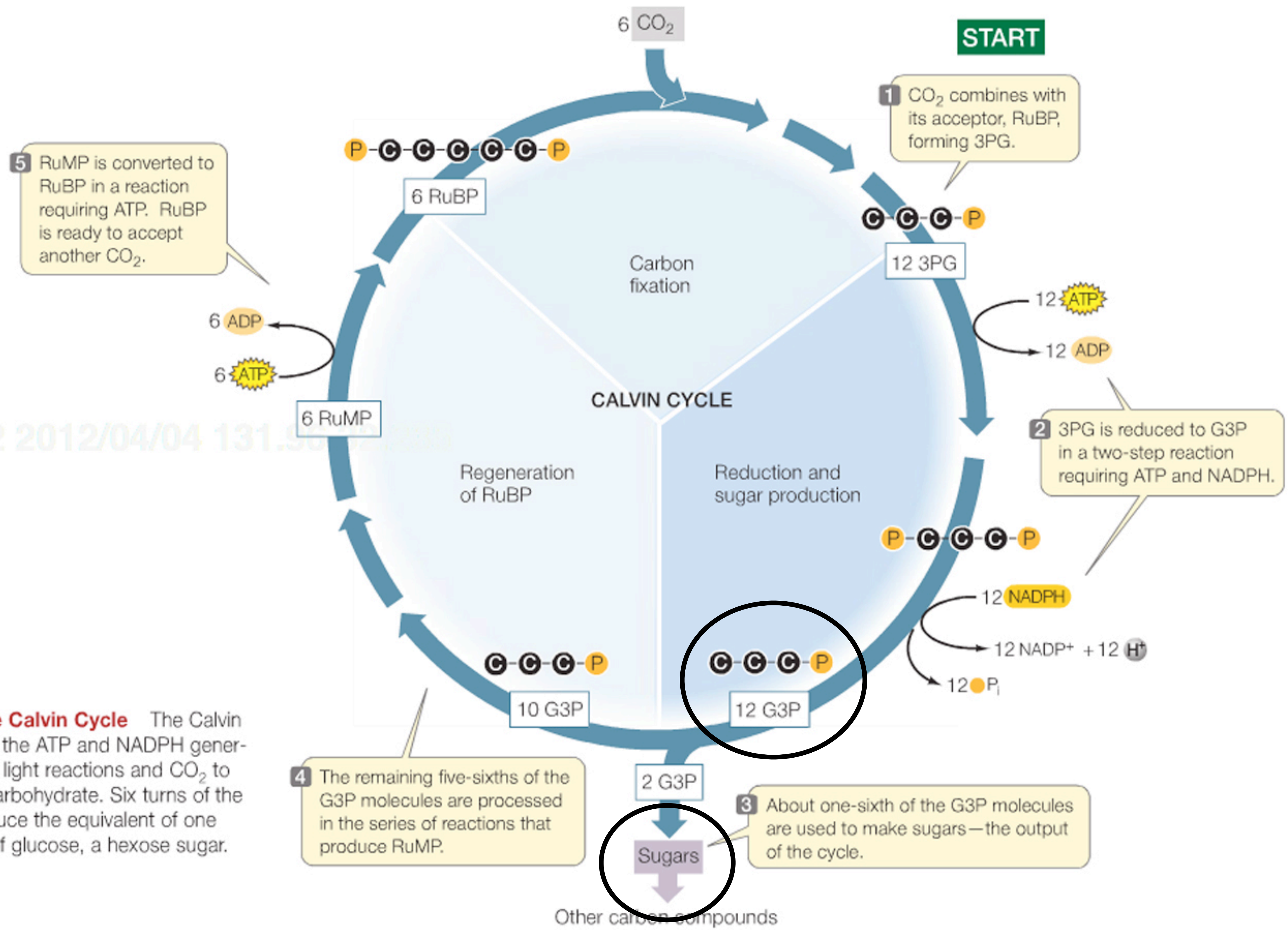
10.15 The Calvin Cycle The Calvin cycle uses the ATP and NADPH generated in the light reactions and CO_2 to produce carbohydrate. Six turns of the cycle produce the equivalent of one molecule of glucose, a hexose sugar.



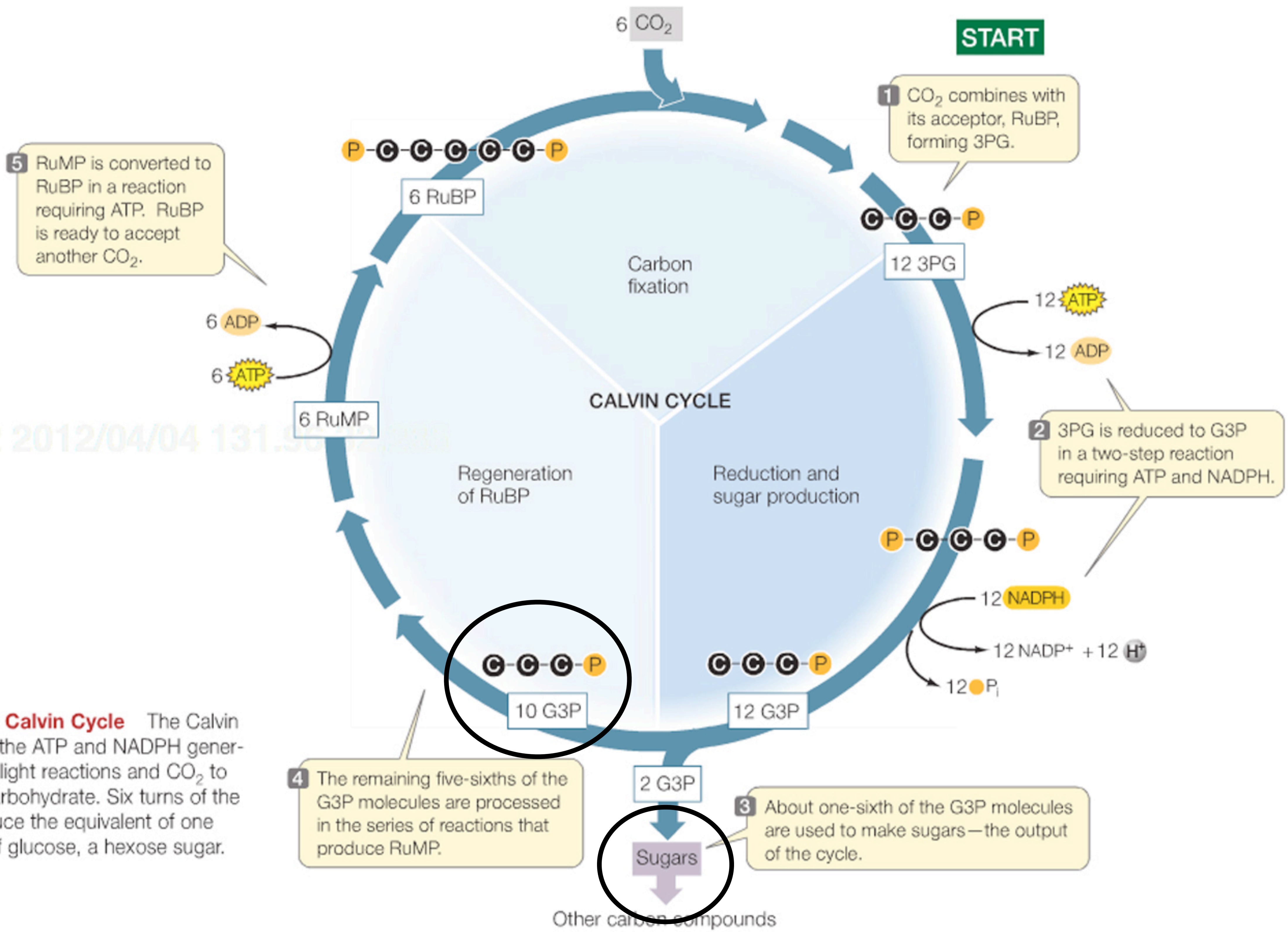
10.15 The Calvin Cycle The Calvin cycle uses the ATP and NADPH generated in the light reactions and CO_2 to produce carbohydrate. Six turns of the cycle produce the equivalent of one molecule of glucose, a hexose sugar.



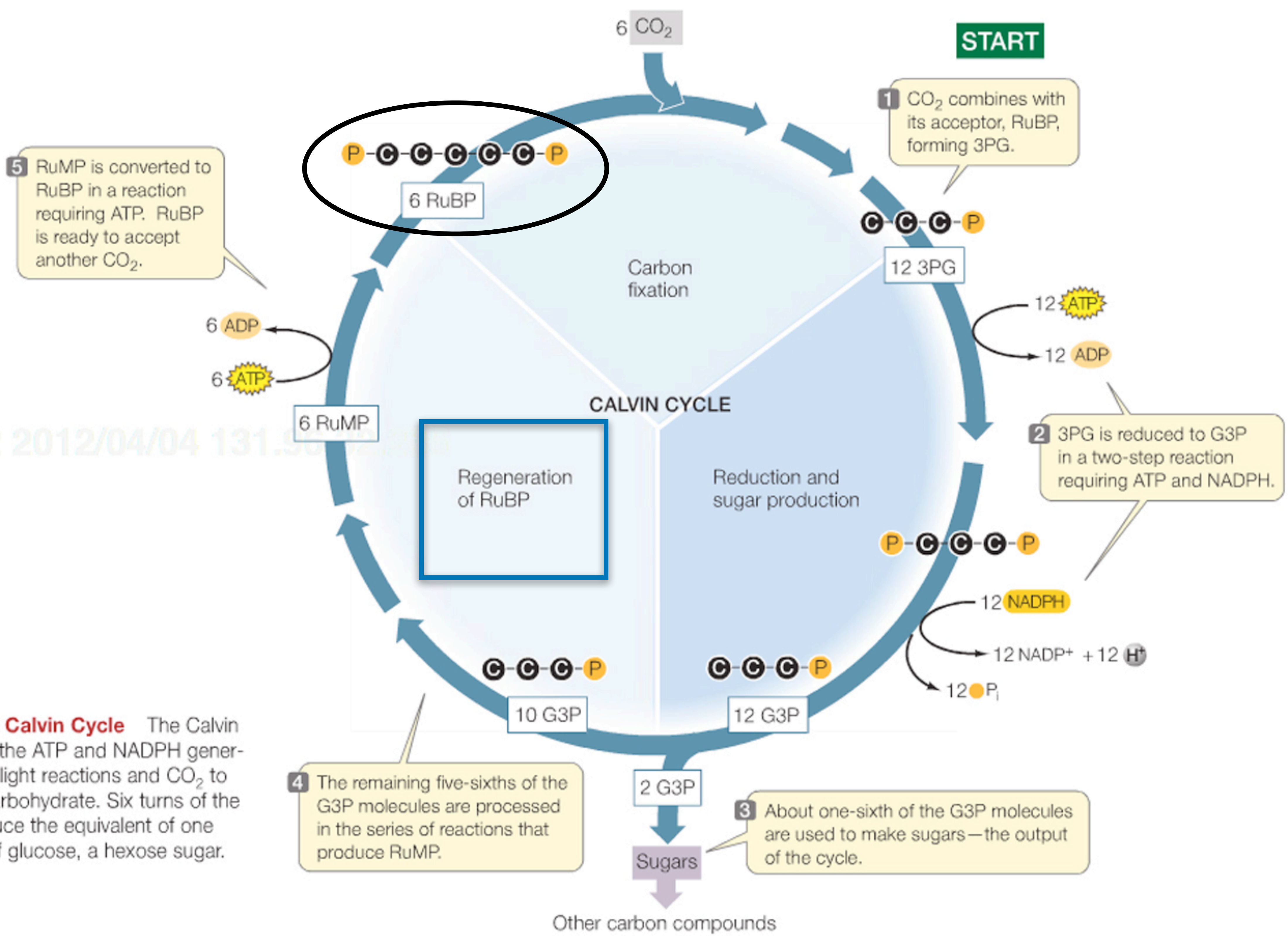
10.15 The Calvin Cycle The Calvin cycle uses the ATP and NADPH generated in the light reactions and CO_2 to produce carbohydrate. Six turns of the cycle produce the equivalent of one molecule of glucose, a hexose sugar.



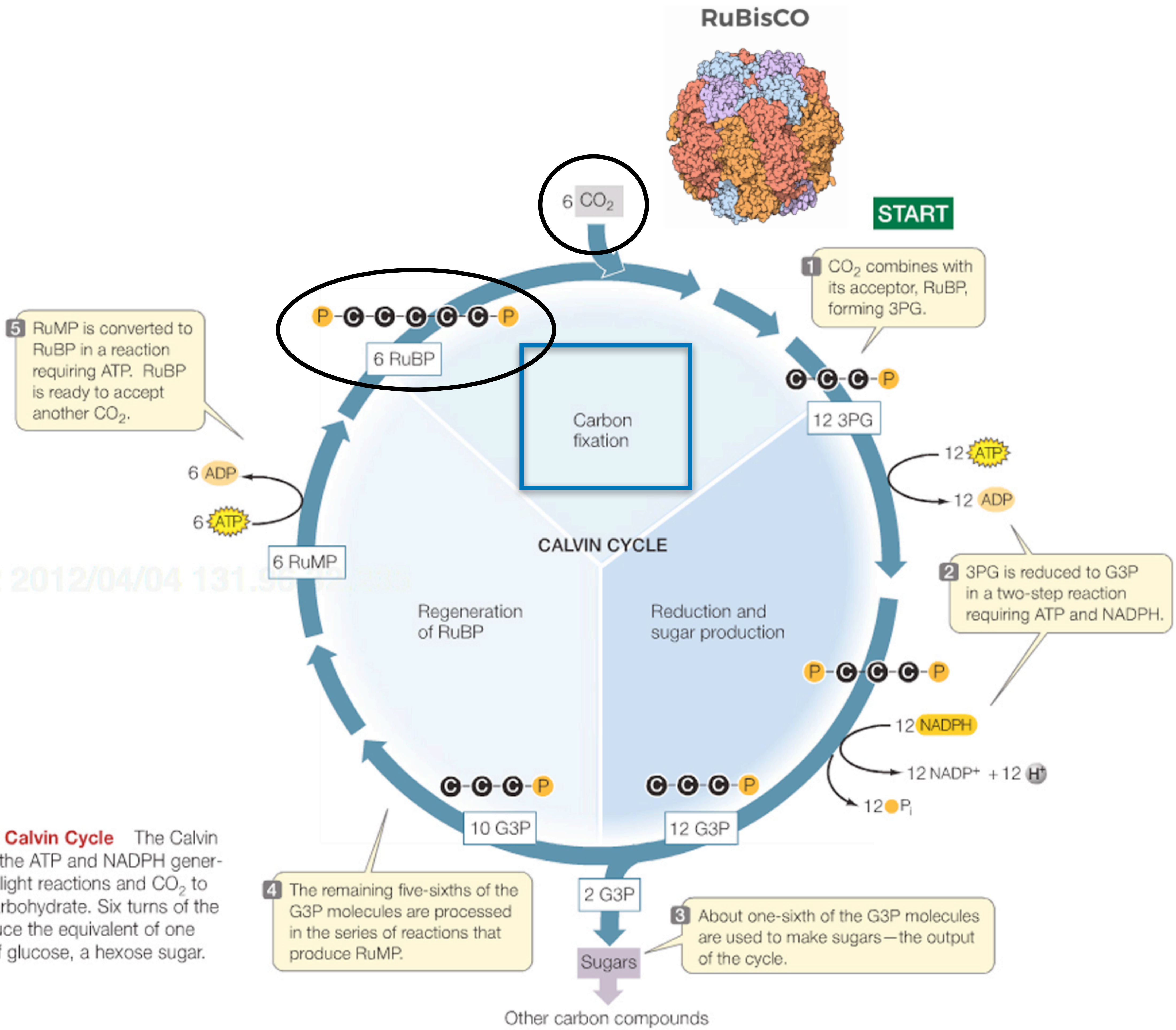
10.15 The Calvin Cycle The Calvin cycle uses the ATP and NADPH generated in the light reactions and CO_2 to produce carbohydrate. Six turns of the cycle produce the equivalent of one molecule of glucose, a hexose sugar.



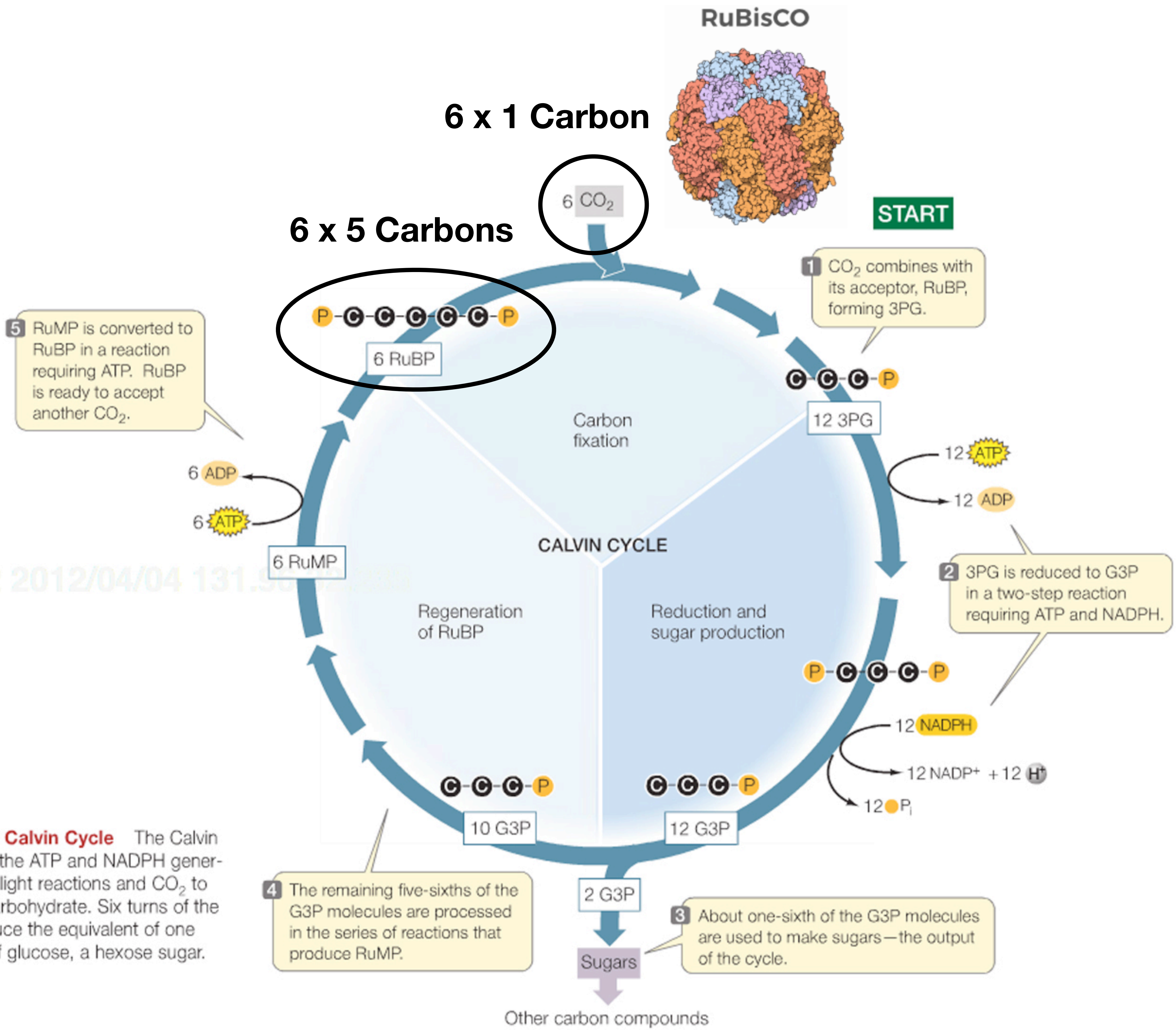
10.15 The Calvin Cycle The Calvin cycle uses the ATP and NADPH generated in the light reactions and CO_2 to produce carbohydrate. Six turns of the cycle produce the equivalent of one molecule of glucose, a hexose sugar.



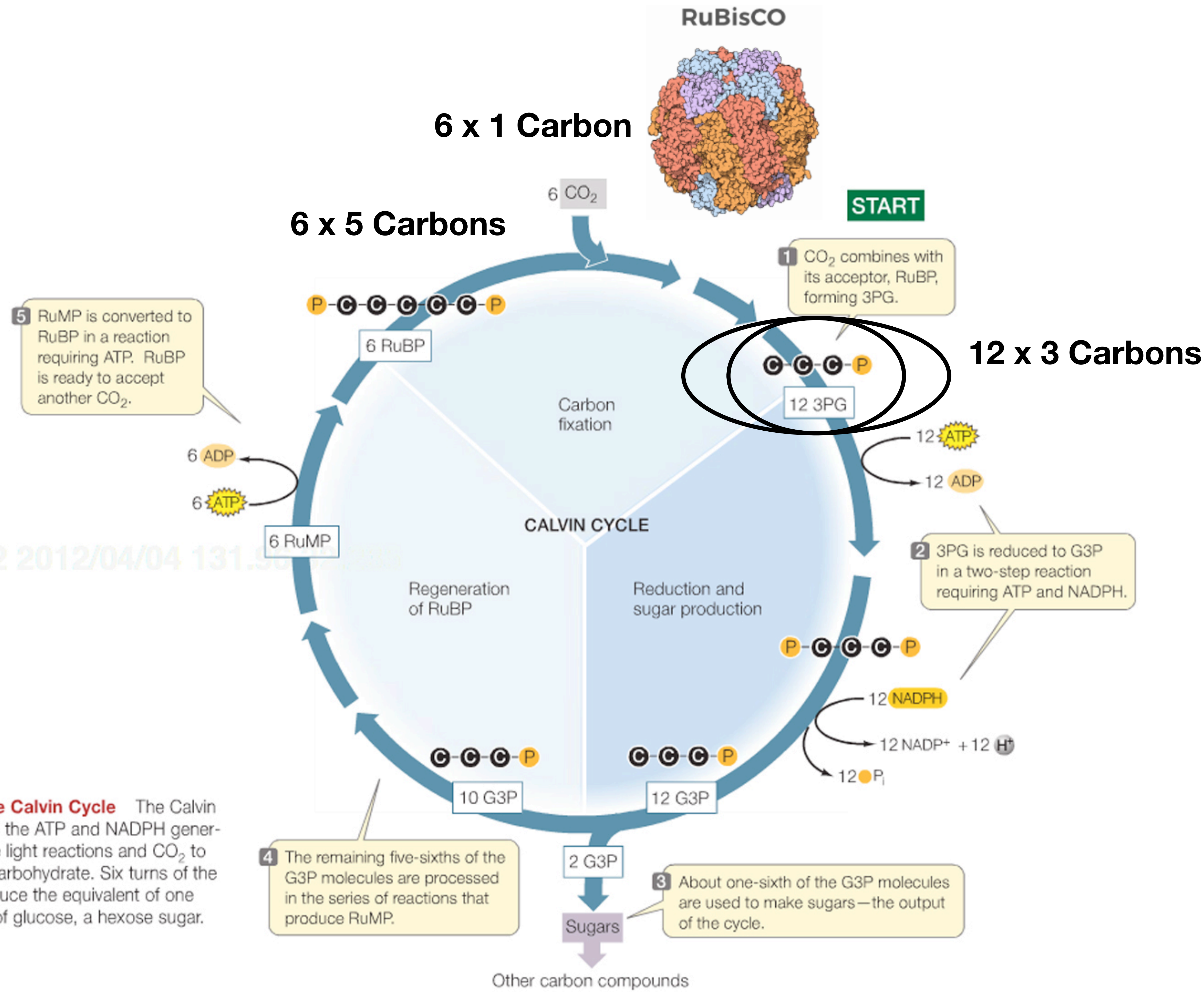
10.15 The Calvin Cycle The Calvin cycle uses the ATP and NADPH generated in the light reactions and CO_2 to produce carbohydrate. Six turns of the cycle produce the equivalent of one molecule of glucose, a hexose sugar.



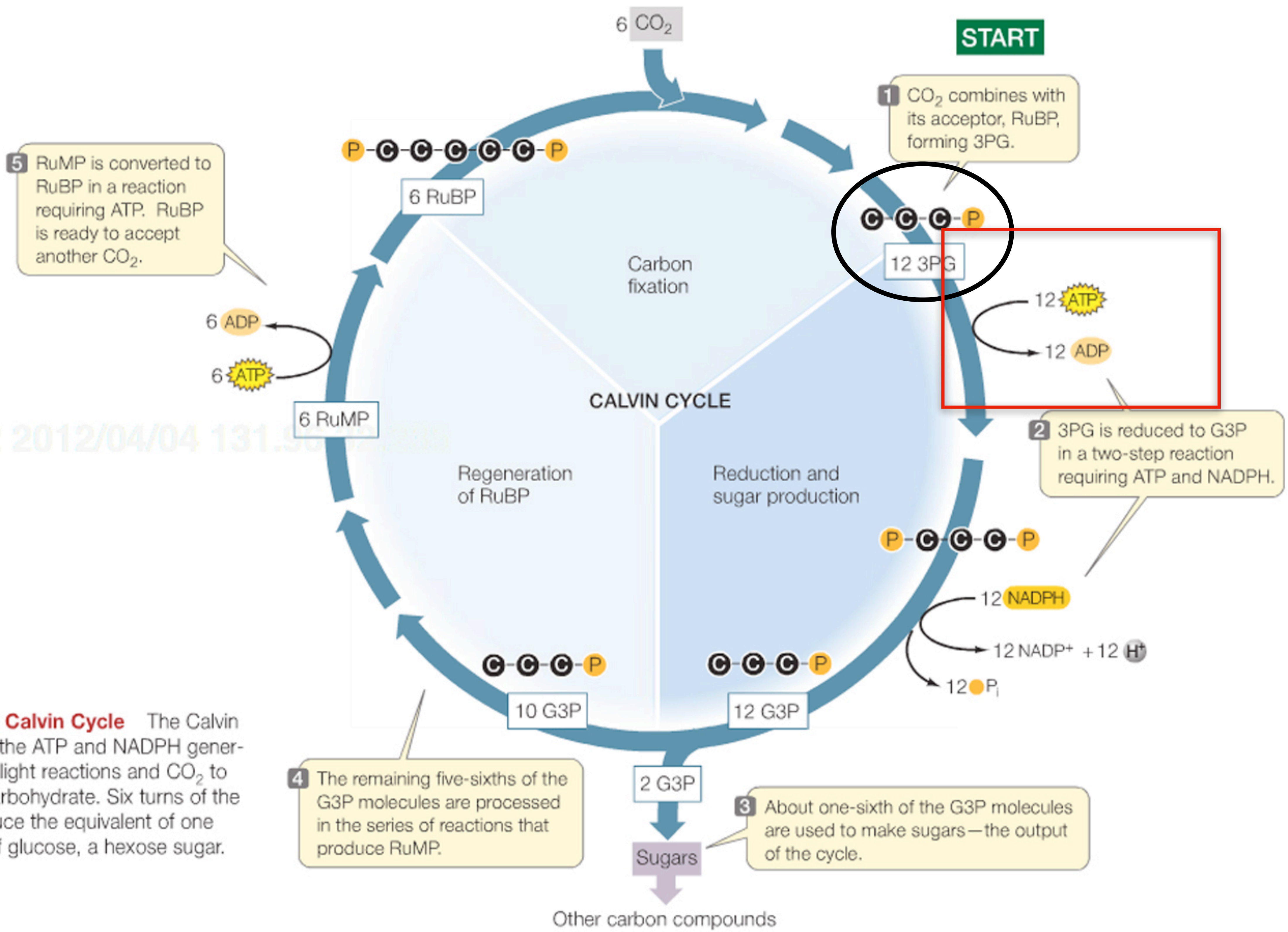
10.15 The Calvin Cycle The Calvin cycle uses the ATP and NADPH generated in the light reactions and CO_2 to produce carbohydrate. Six turns of the cycle produce the equivalent of one molecule of glucose, a hexose sugar.



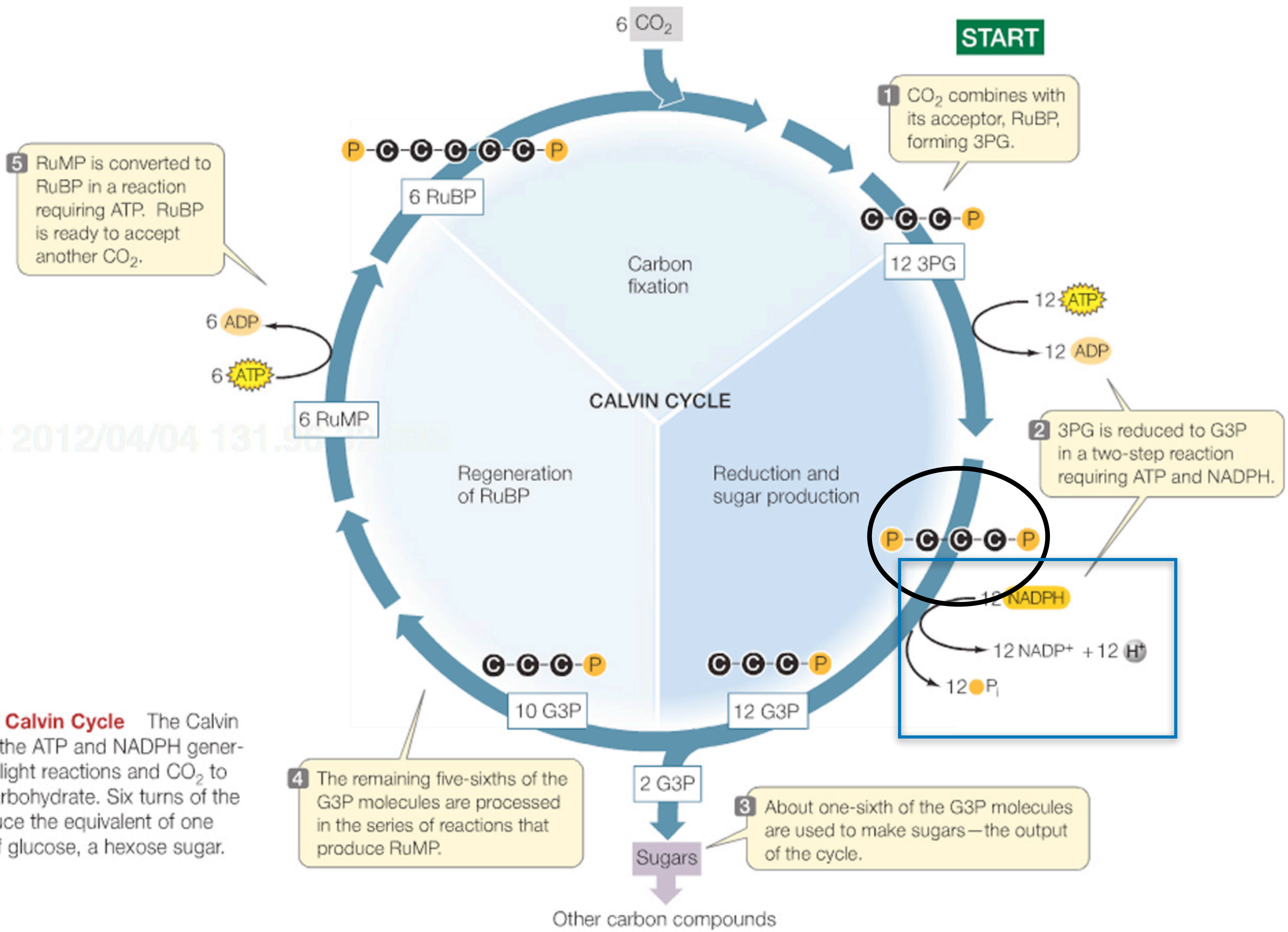
10.15 The Calvin Cycle The Calvin cycle uses the ATP and NADPH generated in the light reactions and CO_2 to produce carbohydrate. Six turns of the cycle produce the equivalent of one molecule of glucose, a hexose sugar.



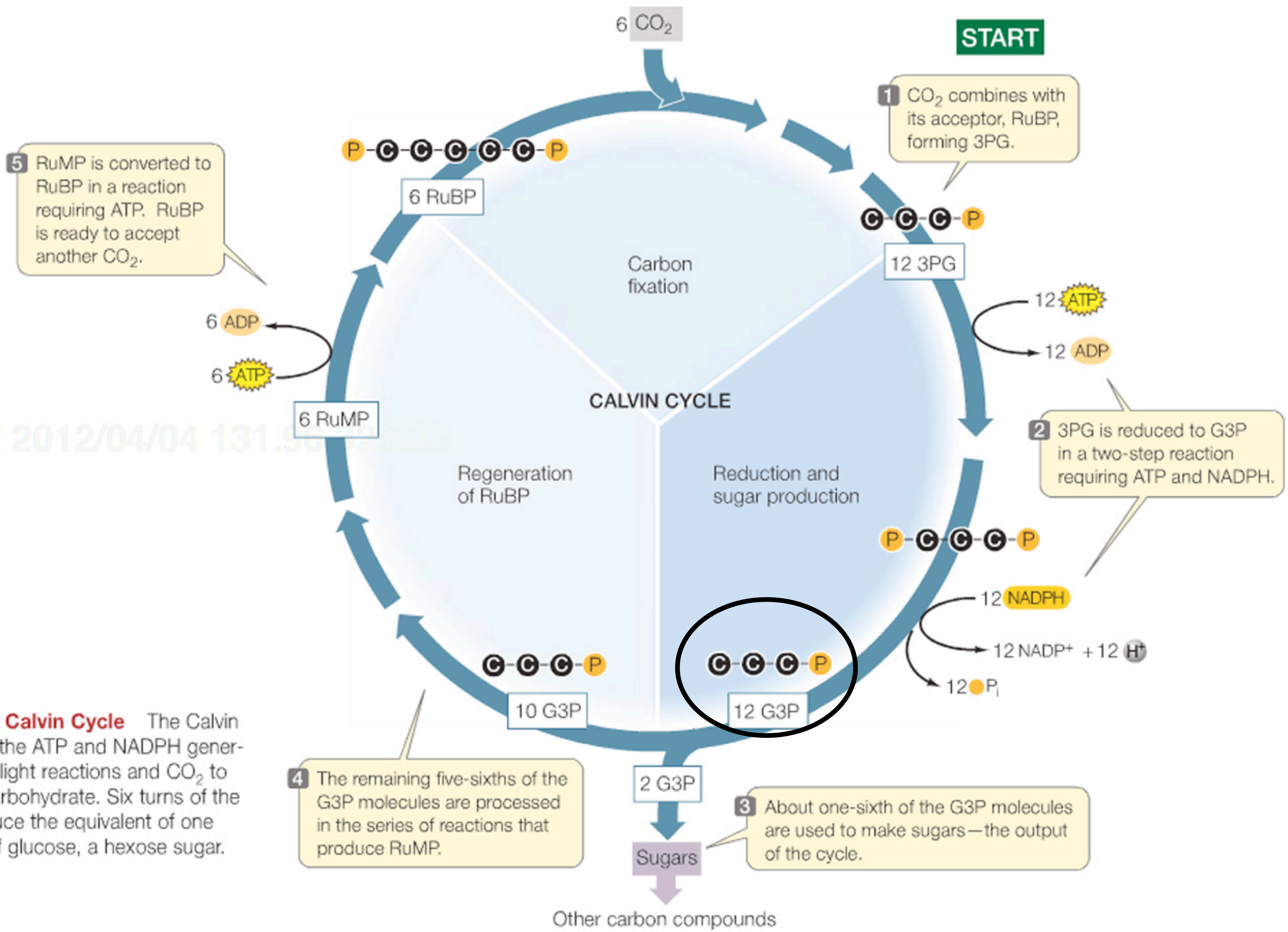
10.15 The Calvin Cycle The Calvin cycle uses the ATP and NADPH generated in the light reactions and CO_2 to produce carbohydrate. Six turns of the cycle produce the equivalent of one molecule of glucose, a hexose sugar.



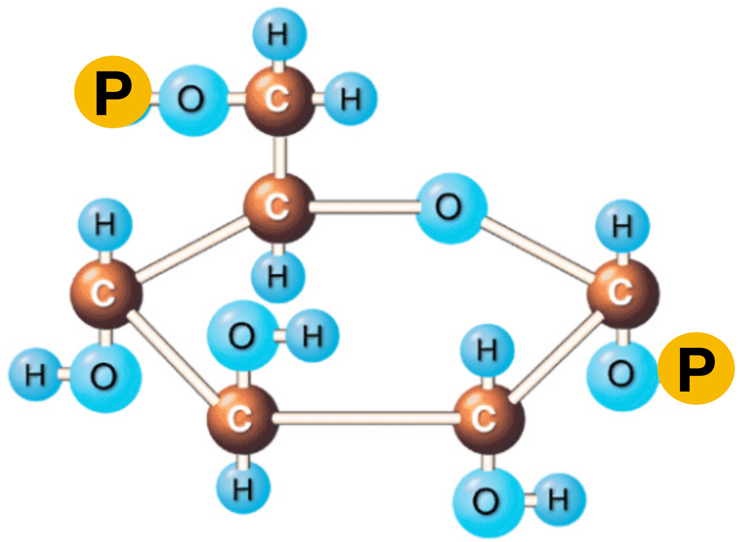
10.15 The Calvin Cycle The Calvin cycle uses the ATP and NADPH generated in the light reactions and CO_2 to produce carbohydrate. Six turns of the cycle produce the equivalent of one molecule of glucose, a hexose sugar.



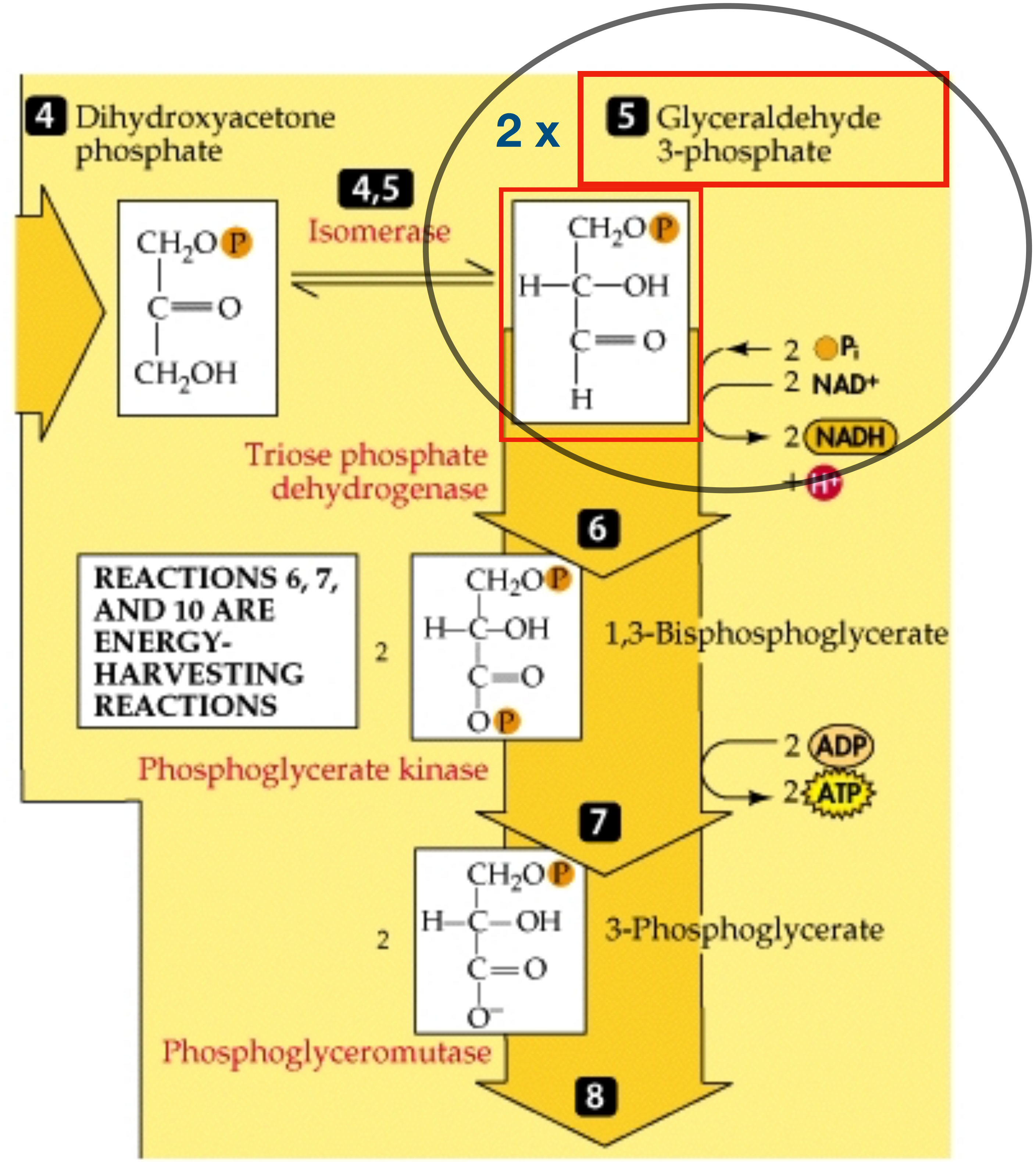
10.15 The Calvin Cycle The Calvin cycle uses the ATP and NADPH generated in the light reactions and CO_2 to produce carbohydrate. Six turns of the cycle produce the equivalent of one molecule of glucose, a hexose sugar.



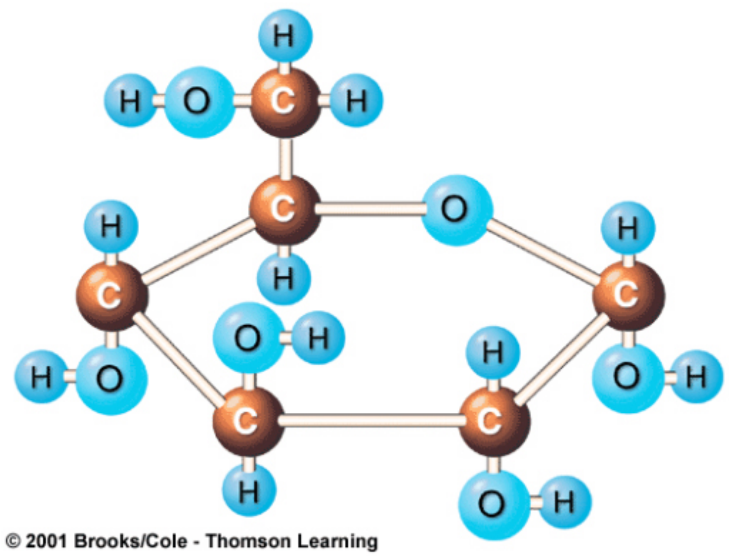
10.15 The Calvin Cycle The Calvin cycle uses the ATP and NADPH generated in the light reactions and CO_2 to produce carbohydrate. Six turns of the cycle produce the equivalent of one molecule of glucose, a hexose sugar.



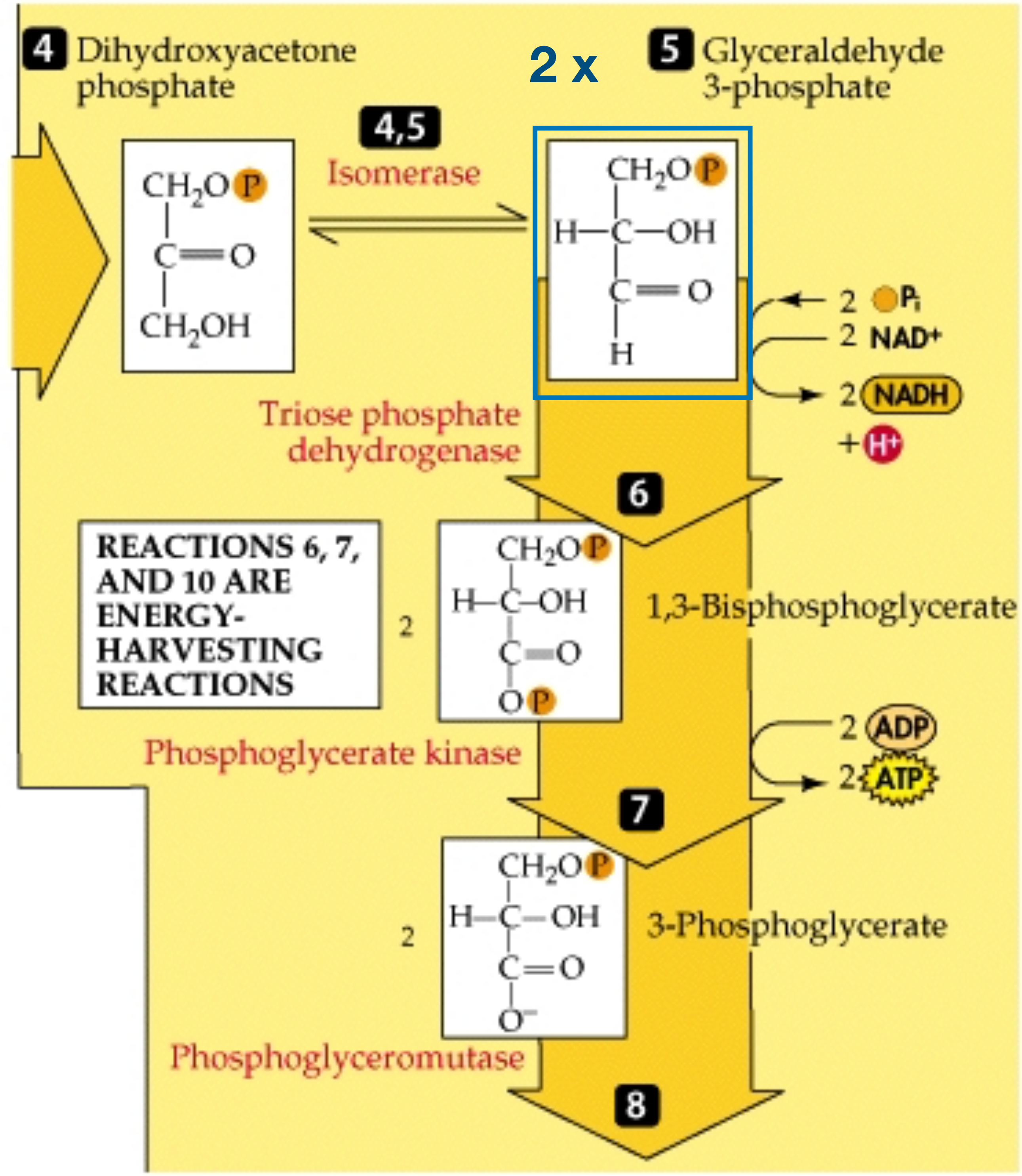
P
P

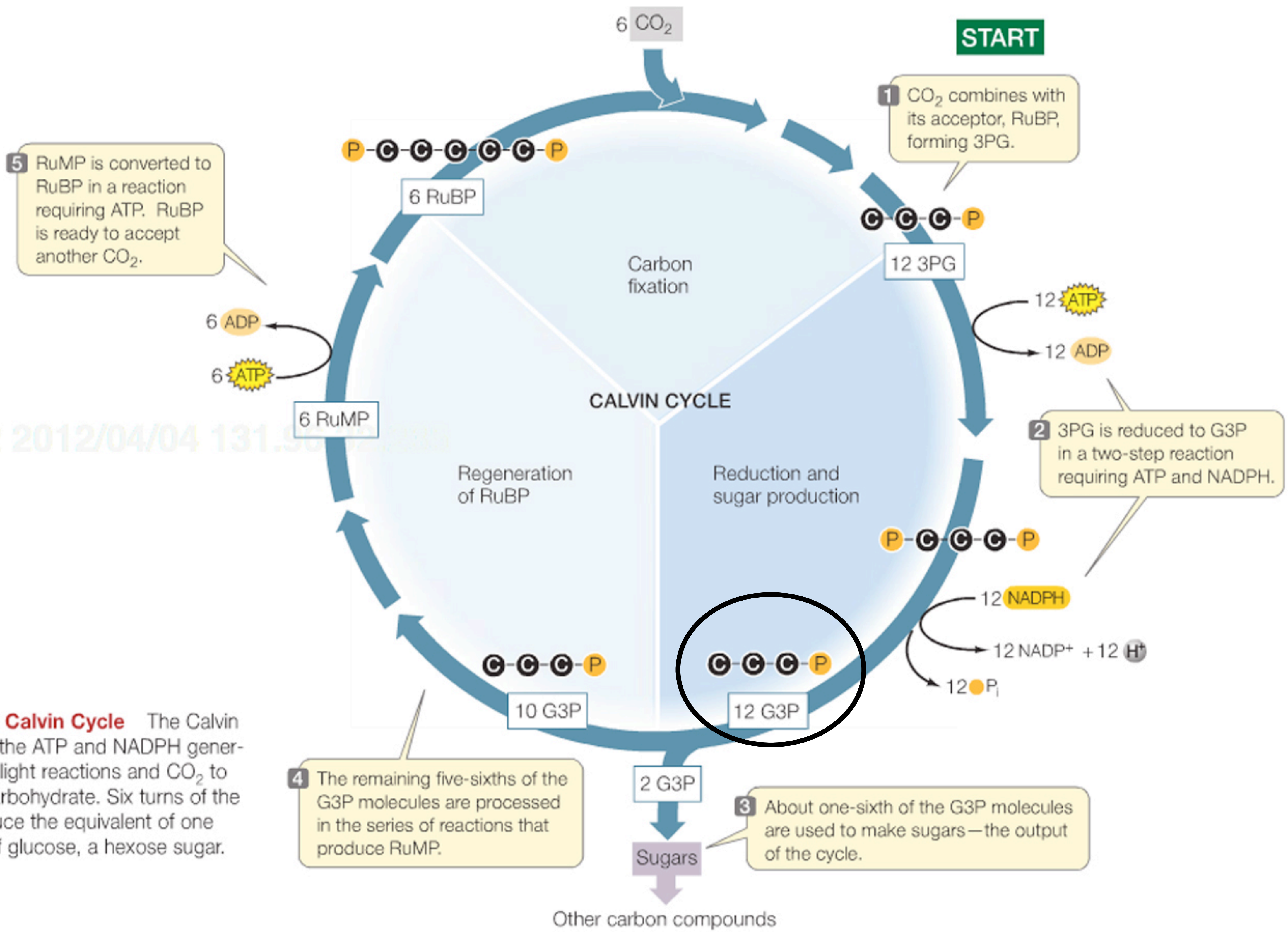


2 x
4 Dihydroxyacetone phosphate
5 Glyceraldehyde 3-phosphate
4,5
Isomerase
Triose phosphate dehydrogenase
2 Pi
2 NAD+
2 NADH
+ H+
6
REACTIONS 6, 7, AND 10 ARE ENERGY-HARVESTING REACTIONS
2
1,3-Bisphosphoglycerate
Phosphoglycerate kinase
2 ADP
2 ATP
7
2
3-Phosphoglycerate
Phosphoglyceromutase
8

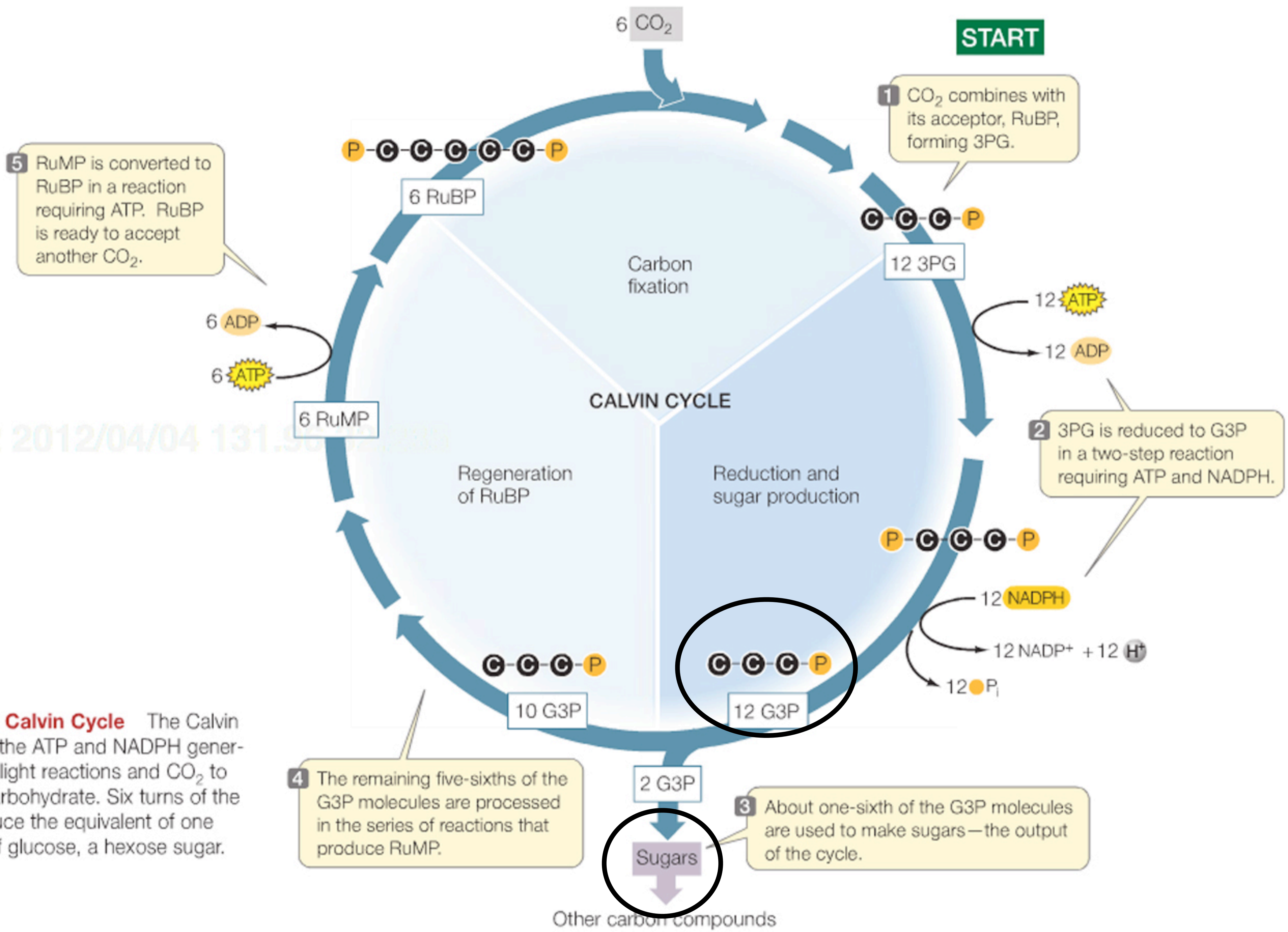

H
O
C
H
H
C
O
H
H
C
H
O
H
O
H
C
O
H
H
C
C
H
O
H

GLUCOSE


4 Dihydroxyacetone phosphate
2 x
5 Glyceraldehyde 3-phosphate
4,5
Isomerase
CH$_2$OP
C=O
CH$_2$OH
CH$_2$OP
H—C—OH
C=O
H
2 Pi
2 NAD+
2 NADH
+ H+
Triose phosphate dehydrogenase
6
REACTIONS 6, 7, AND 10 ARE ENERGY-HARVESTING REACTIONS
2
CH$_2$OP
H—C—OH
C=O
OP
1,3-Bisphosphoglycerate
2 ADP
2 ATP
Phosphoglycerate kinase
7
2
CH$_2$OP
H—C—OH
C=O
O$^-$
3-Phosphoglycerate
Phosphoglyceromutase
8



10.15 The Calvin Cycle The Calvin cycle uses the ATP and NADPH generated in the light reactions and CO_2 to produce carbohydrate. Six turns of the cycle produce the equivalent of one molecule of glucose, a hexose sugar.

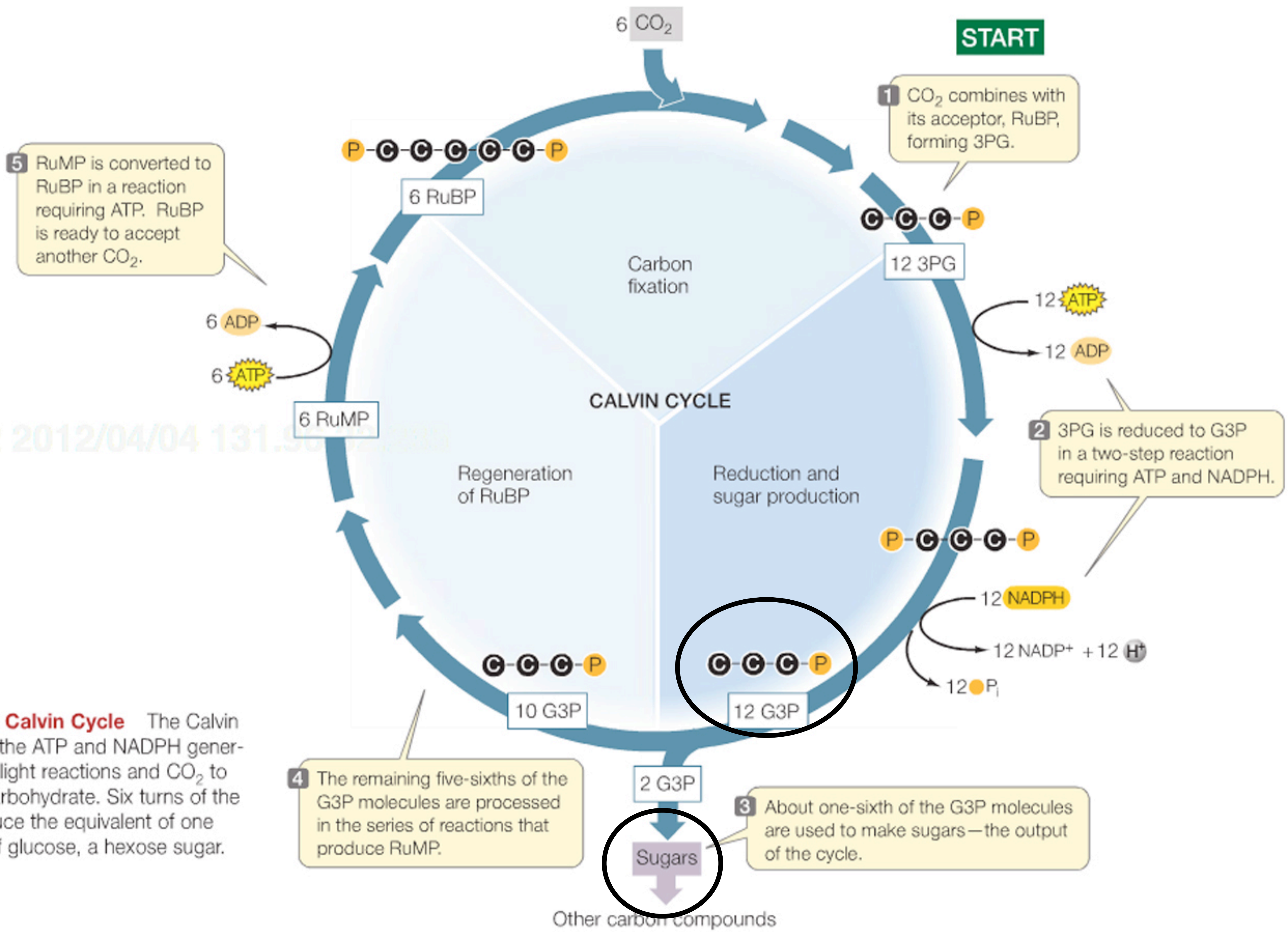


10.15 The Calvin Cycle The Calvin cycle uses the ATP and NADPH generated in the light reactions and CO_2 to produce carbohydrate. Six turns of the cycle produce the equivalent of one molecule of glucose, a hexose sugar.

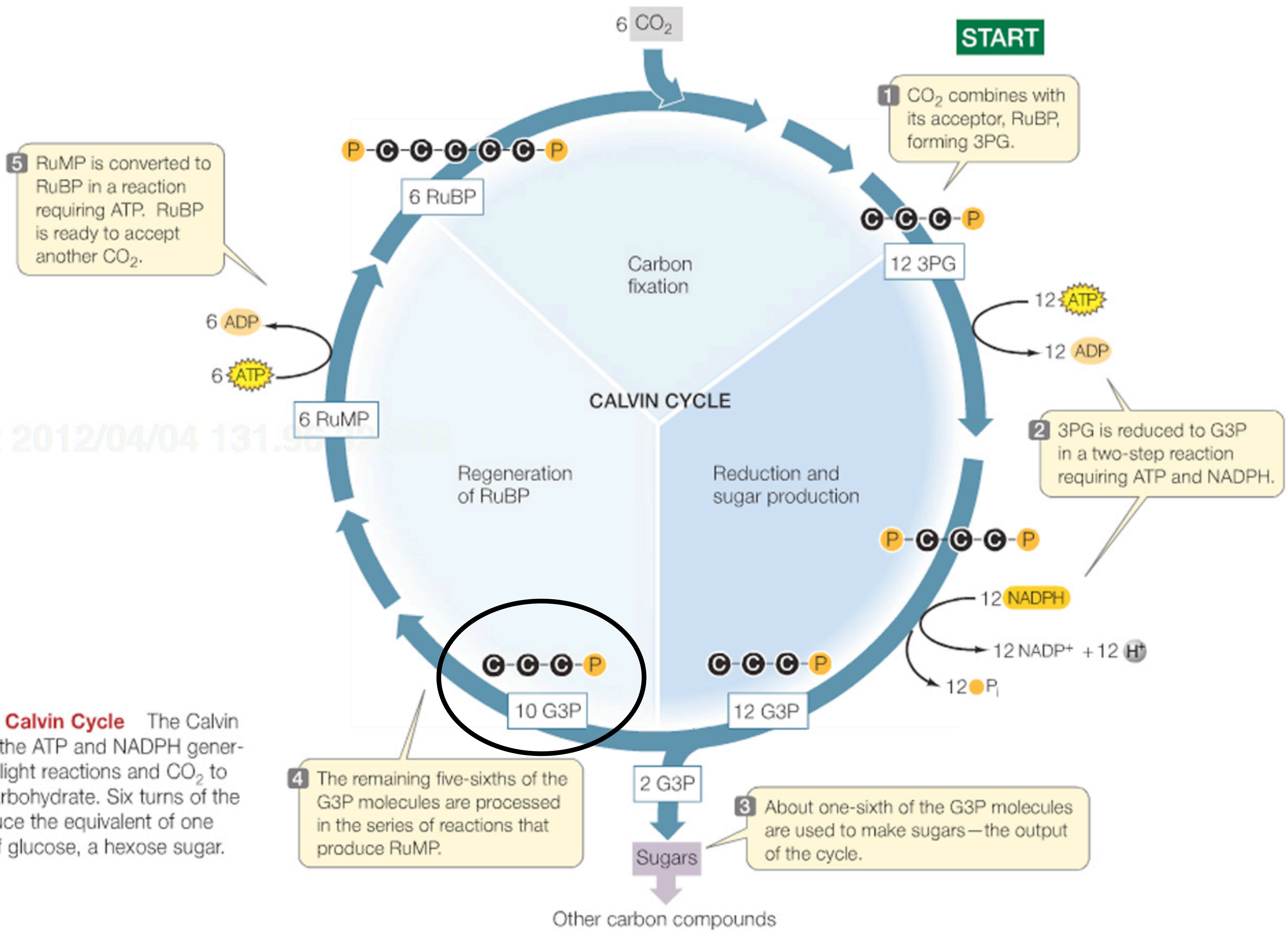
There are two fates for the **2 x G3P** that are produced:

~ **1/3** ends up as **STARCH**, which is stored in the chloroplast and serves as a future source of... you guessed it, glucose.

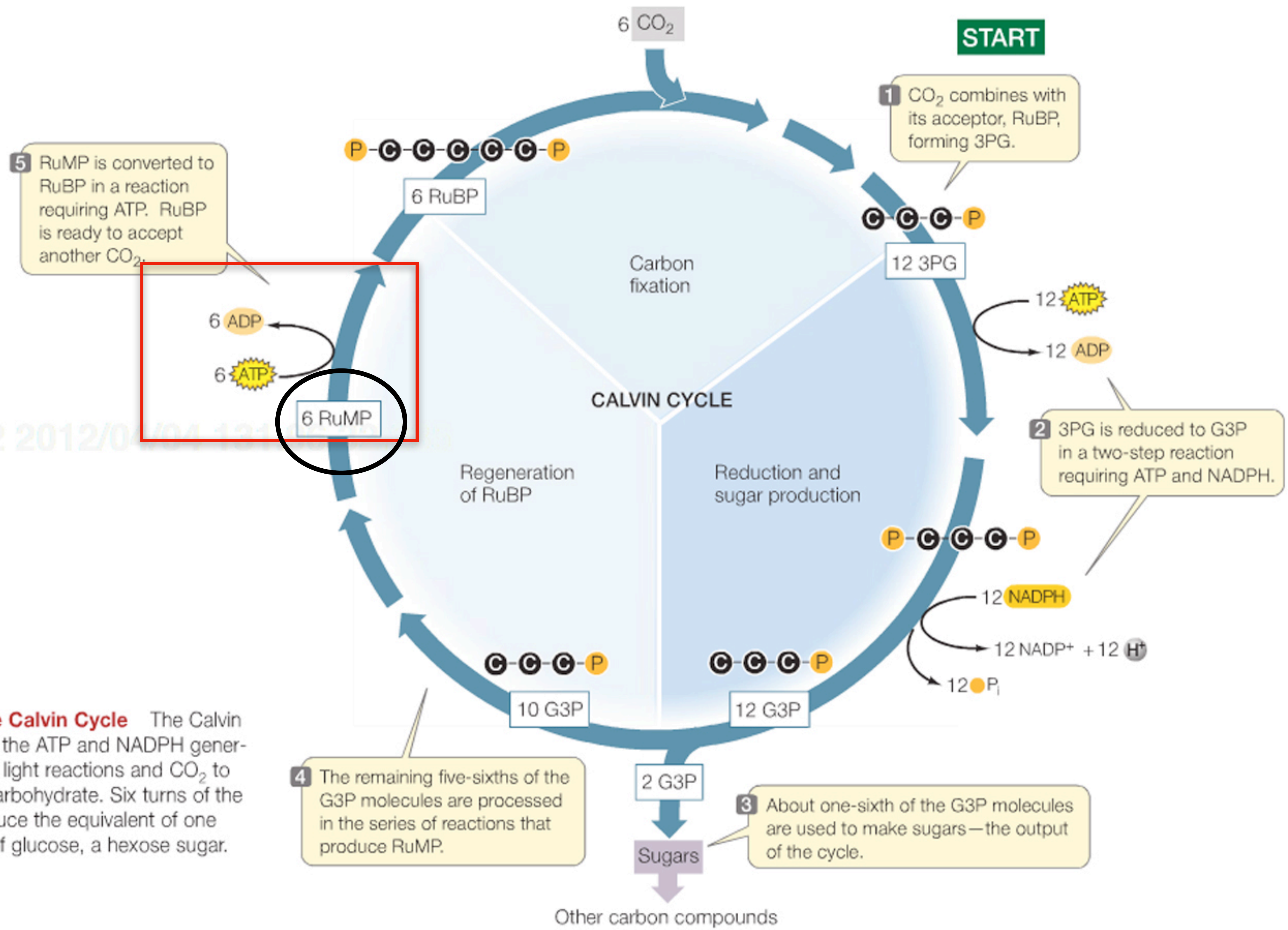
~ **2/3** is converted directly into **glucose** to provide a source of energy for generic cellular energy.



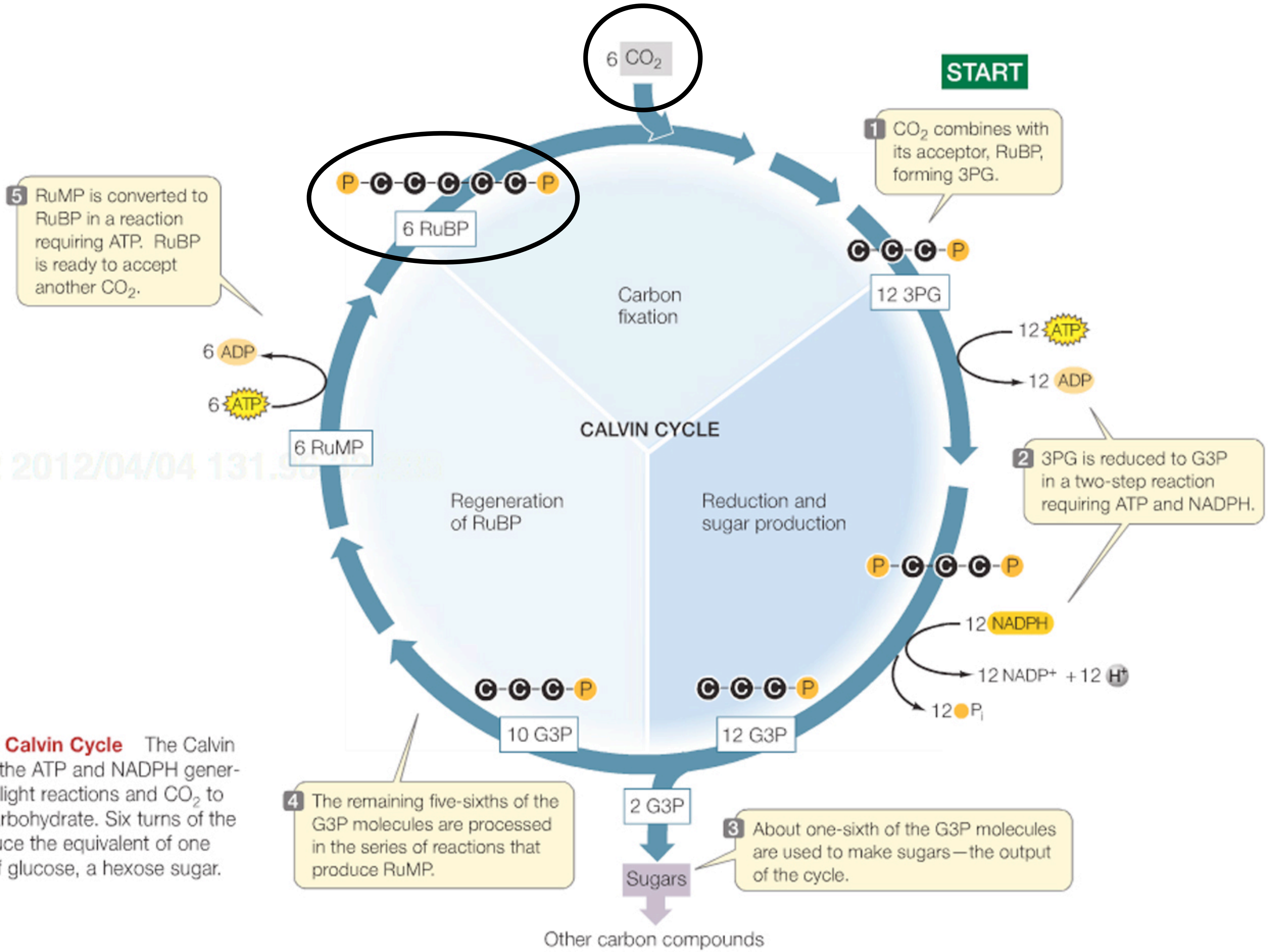
10.15 The Calvin Cycle The Calvin cycle uses the ATP and NADPH generated in the light reactions and CO_2 to produce carbohydrate. Six turns of the cycle produce the equivalent of one molecule of glucose, a hexose sugar.



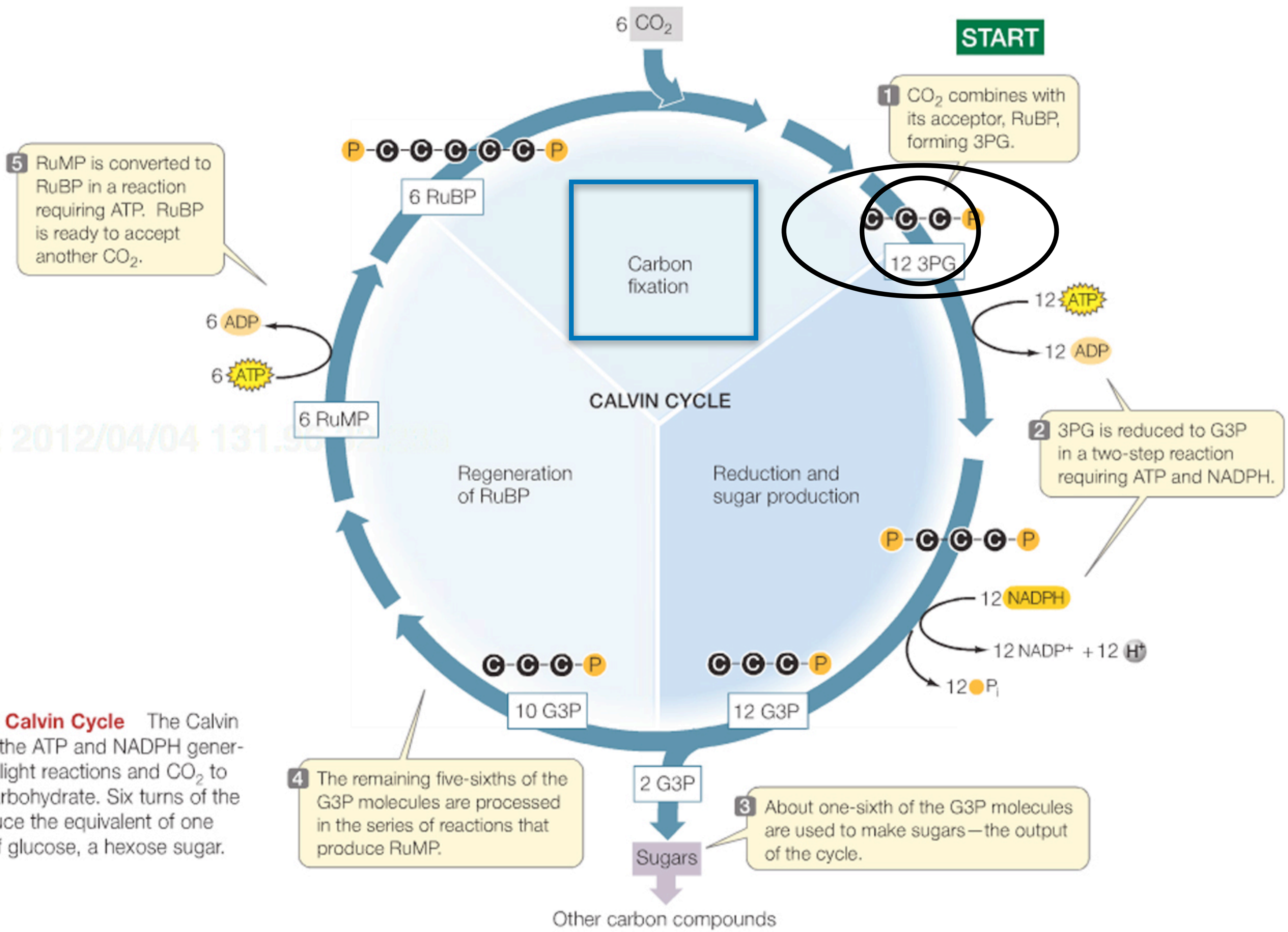
10.15 The Calvin Cycle The Calvin cycle uses the ATP and NADPH generated in the light reactions and CO_2 to produce carbohydrate. Six turns of the cycle produce the equivalent of one molecule of glucose, a hexose sugar.



10.15 The Calvin Cycle The Calvin cycle uses the ATP and NADPH generated in the light reactions and CO_2 to produce carbohydrate. Six turns of the cycle produce the equivalent of one molecule of glucose, a hexose sugar.

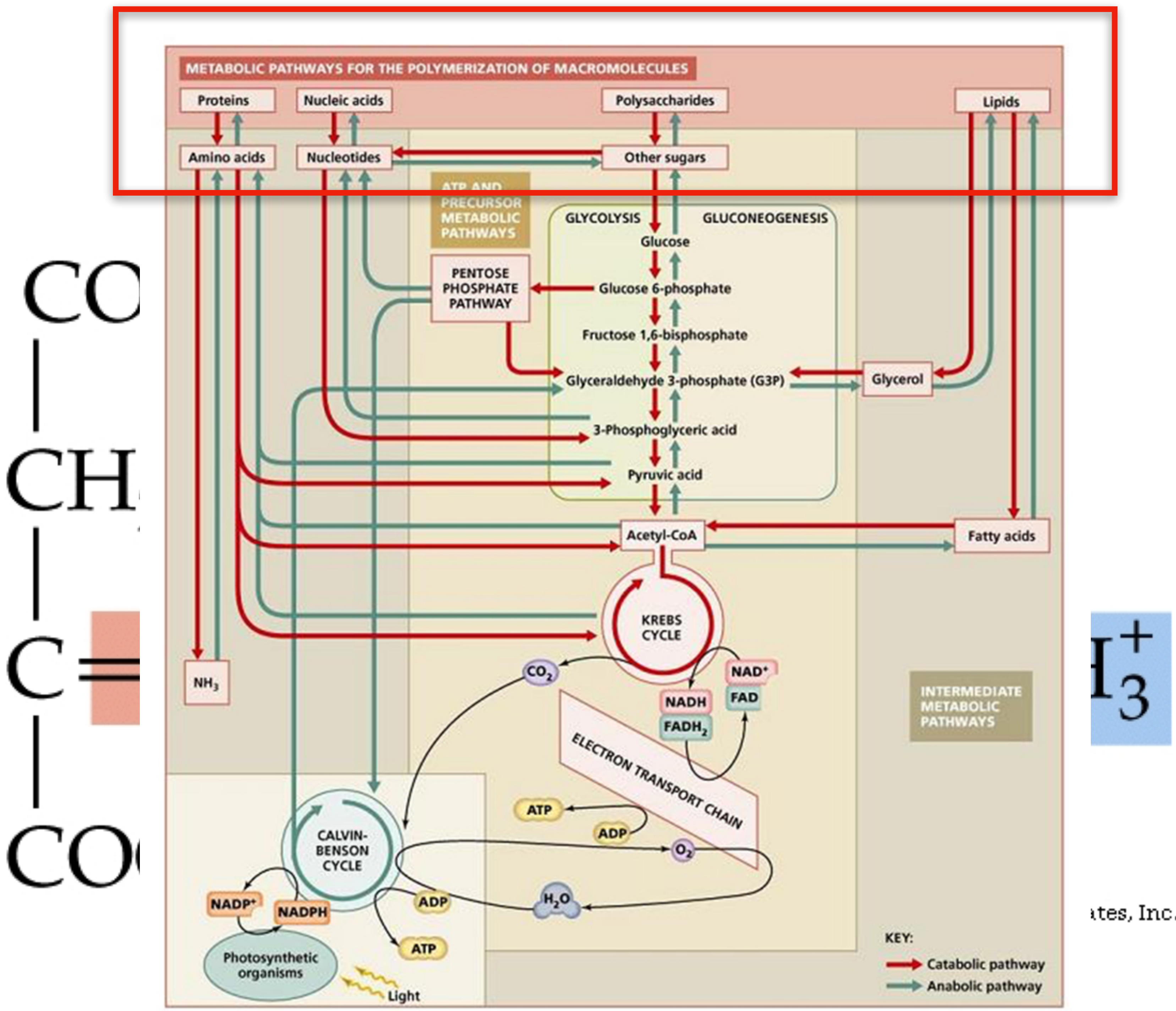


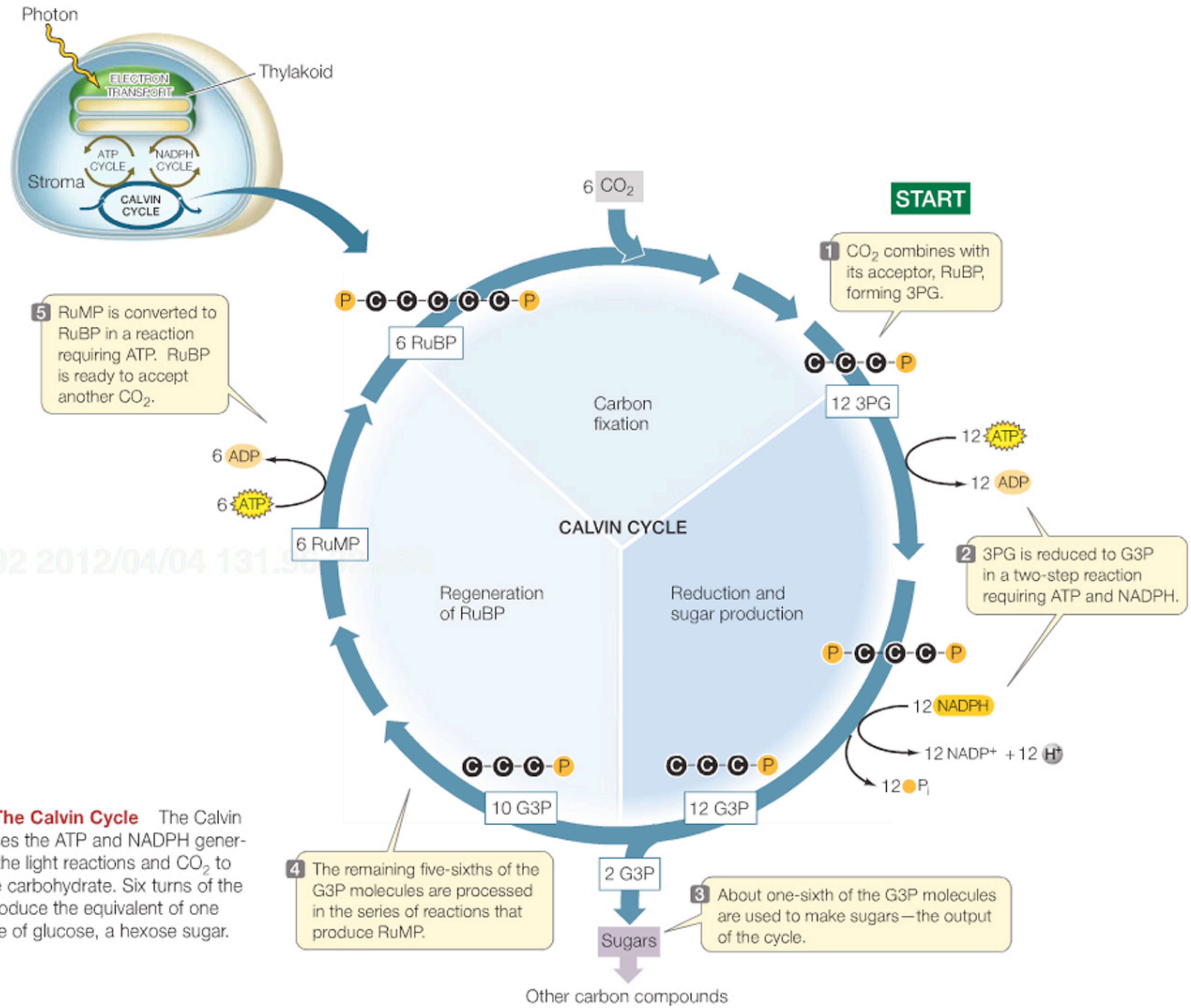
10.15 The Calvin Cycle The Calvin cycle uses the ATP and NADPH generated in the light reactions and CO_2 to produce carbohydrate. Six turns of the cycle produce the equivalent of one molecule of glucose, a hexose sugar.



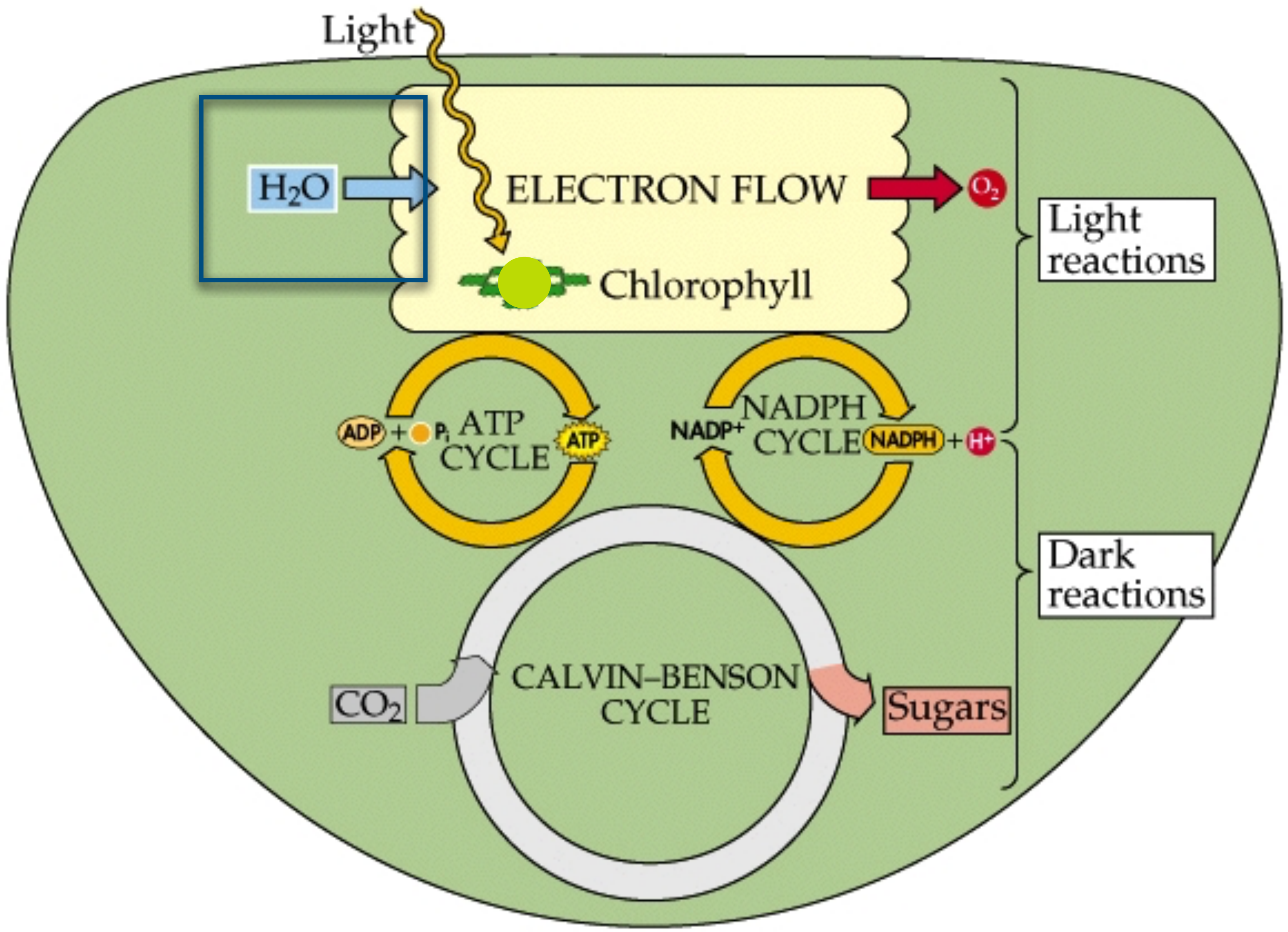
10.15 The Calvin Cycle The Calvin cycle uses the ATP and NADPH generated in the light reactions and CO_2 to produce carbohydrate. Six turns of the cycle produce the equivalent of one molecule of glucose, a hexose sugar.

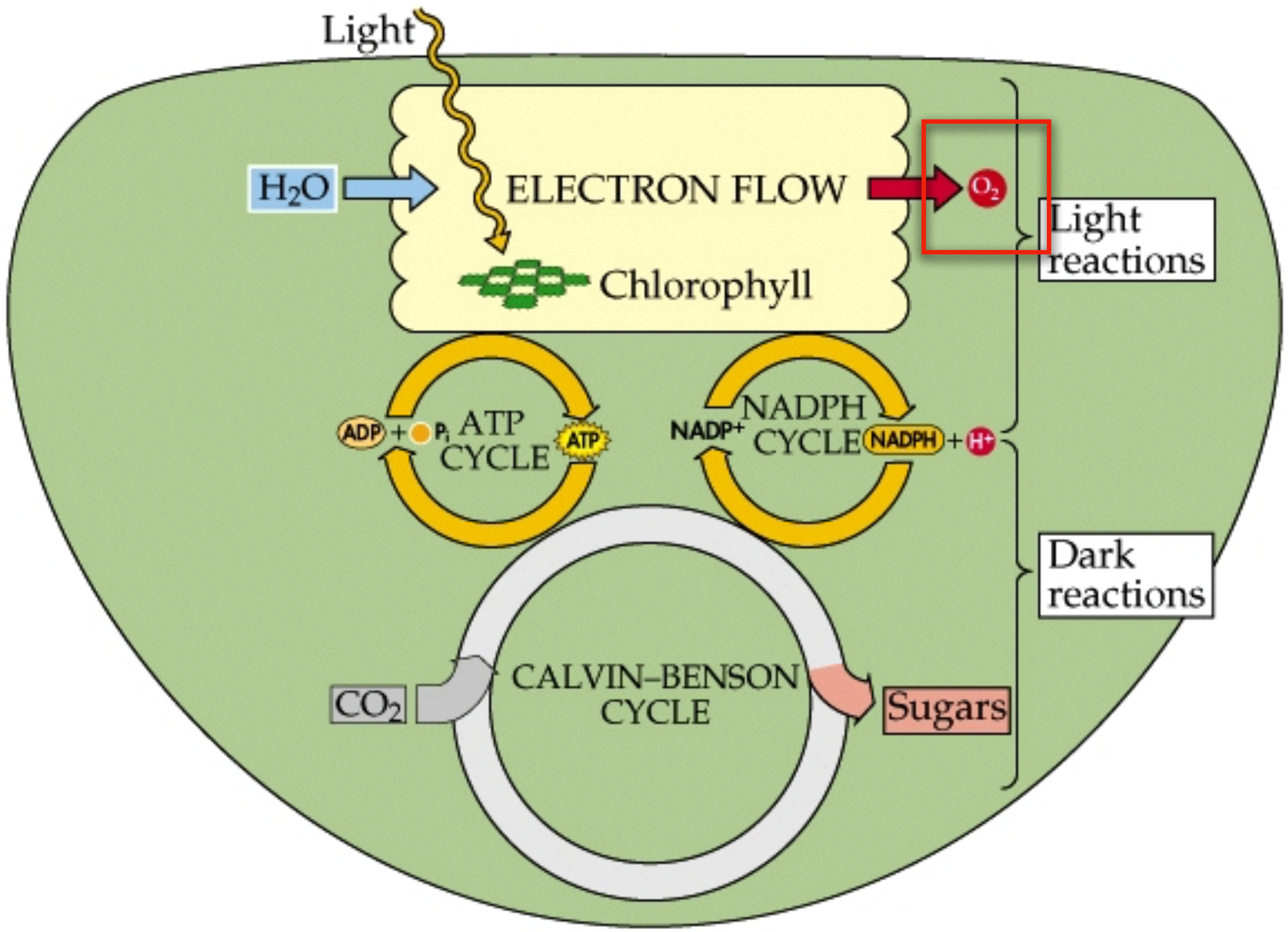
Most of the stored energy is released by the last part of glycolysis during cellular respiration by the plant itself, during growth, development, and reproduction.

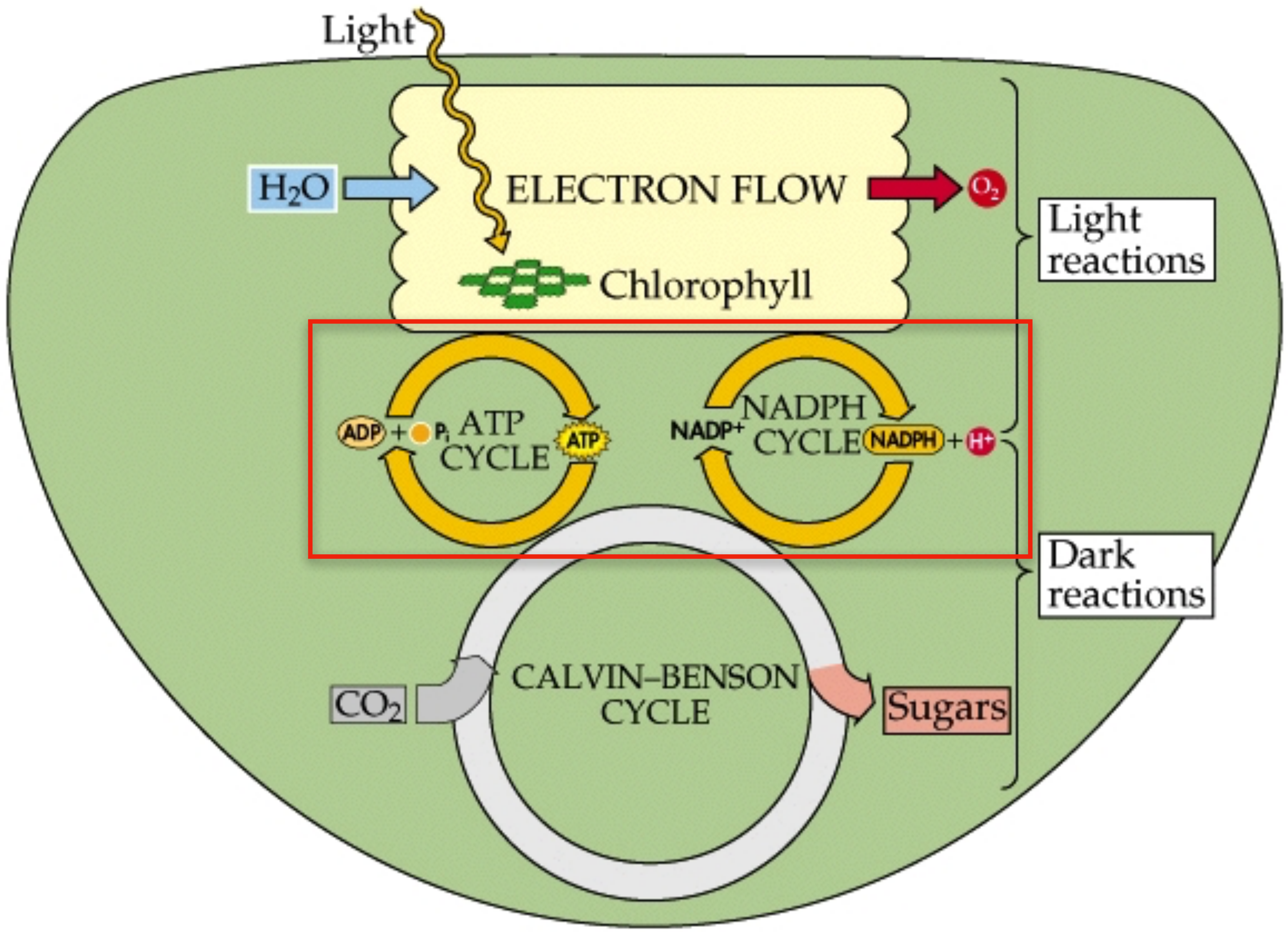




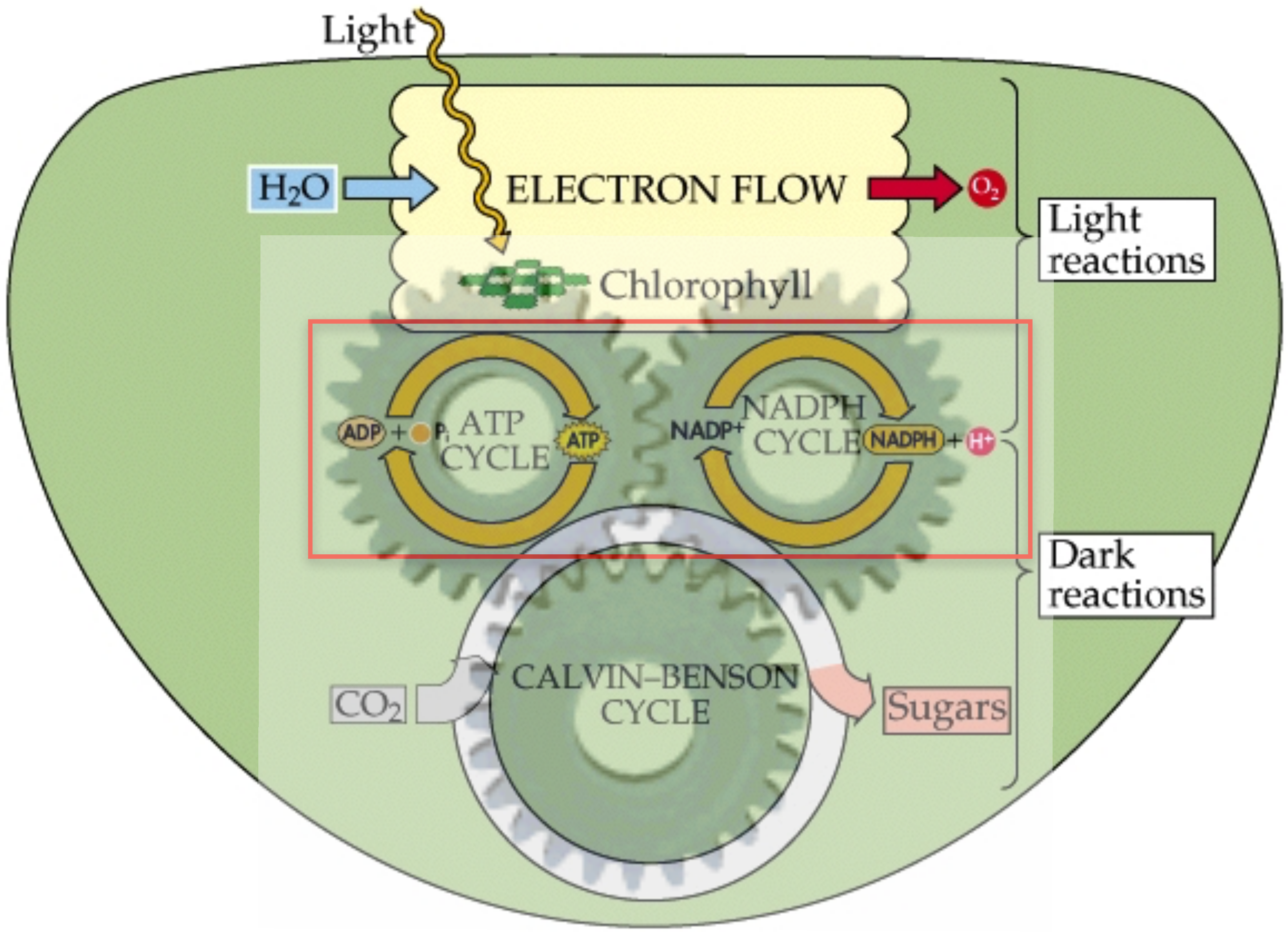
10.15 The Calvin Cycle The Calvin cycle uses the ATP and NADPH generated in the light reactions and CO_2 to produce carbohydrate. Six turns of the cycle produce the equivalent of one molecule of glucose, a hexose sugar.


Light
H_2O
ELECTRON FLOW
O_2
Chlorophyll
Light reactions
ADP
P_i
ATP CYCLE
ATP
NADPH CYCLE
$NADP^+$
NADPH
H^+
Dark reactions
CO_2
CALVIN–BENSON CYCLE
Sugars

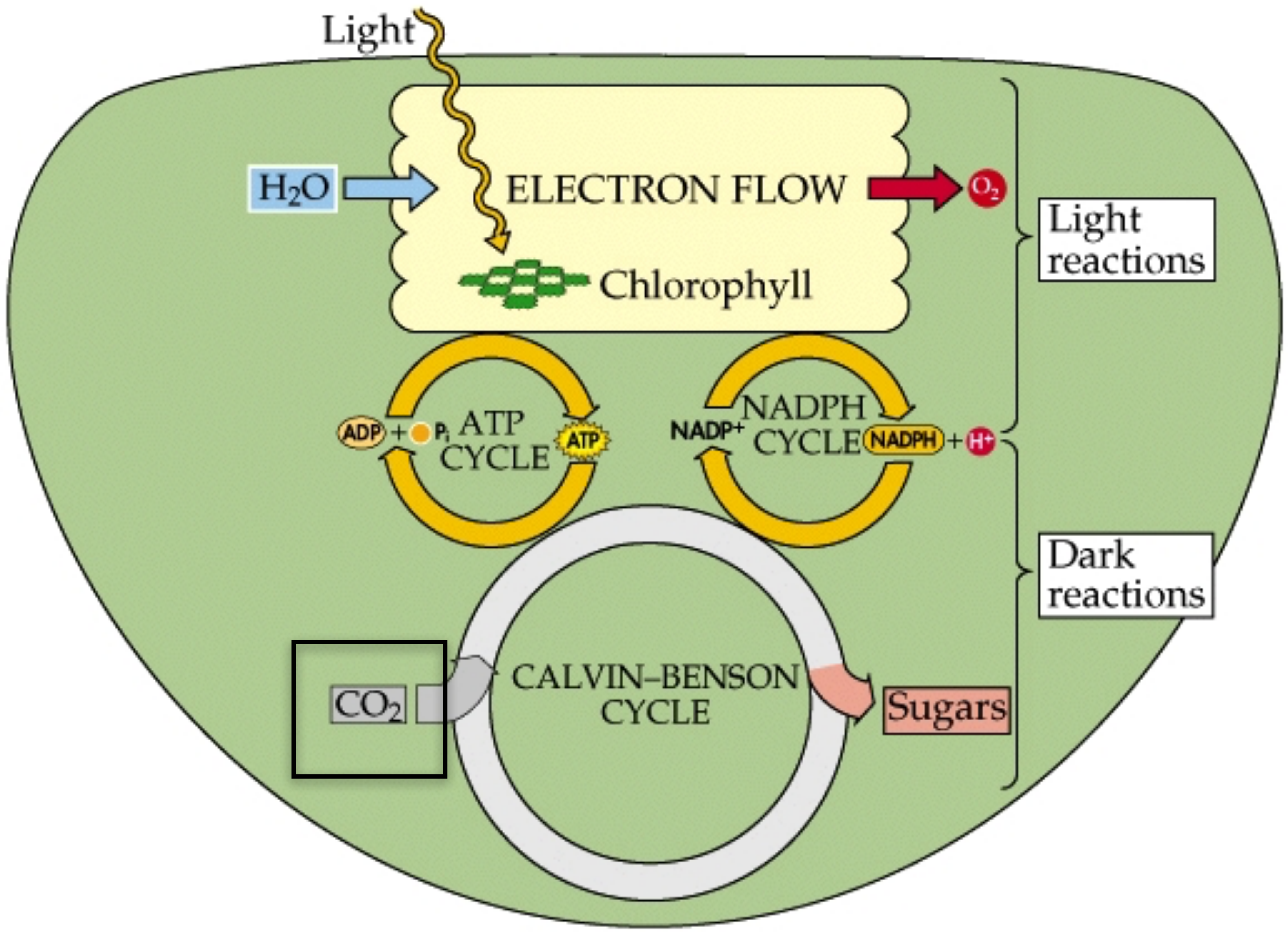

Light
H_2O
ELECTRON FLOW
O_2
Chlorophyll
Light reactions
ADP + P_i
ATP CYCLE
ATP
NADP+
NADPH CYCLE
NADPH + H+
Dark reactions
CO_2
CALVIN–BENSON CYCLE
Sugars

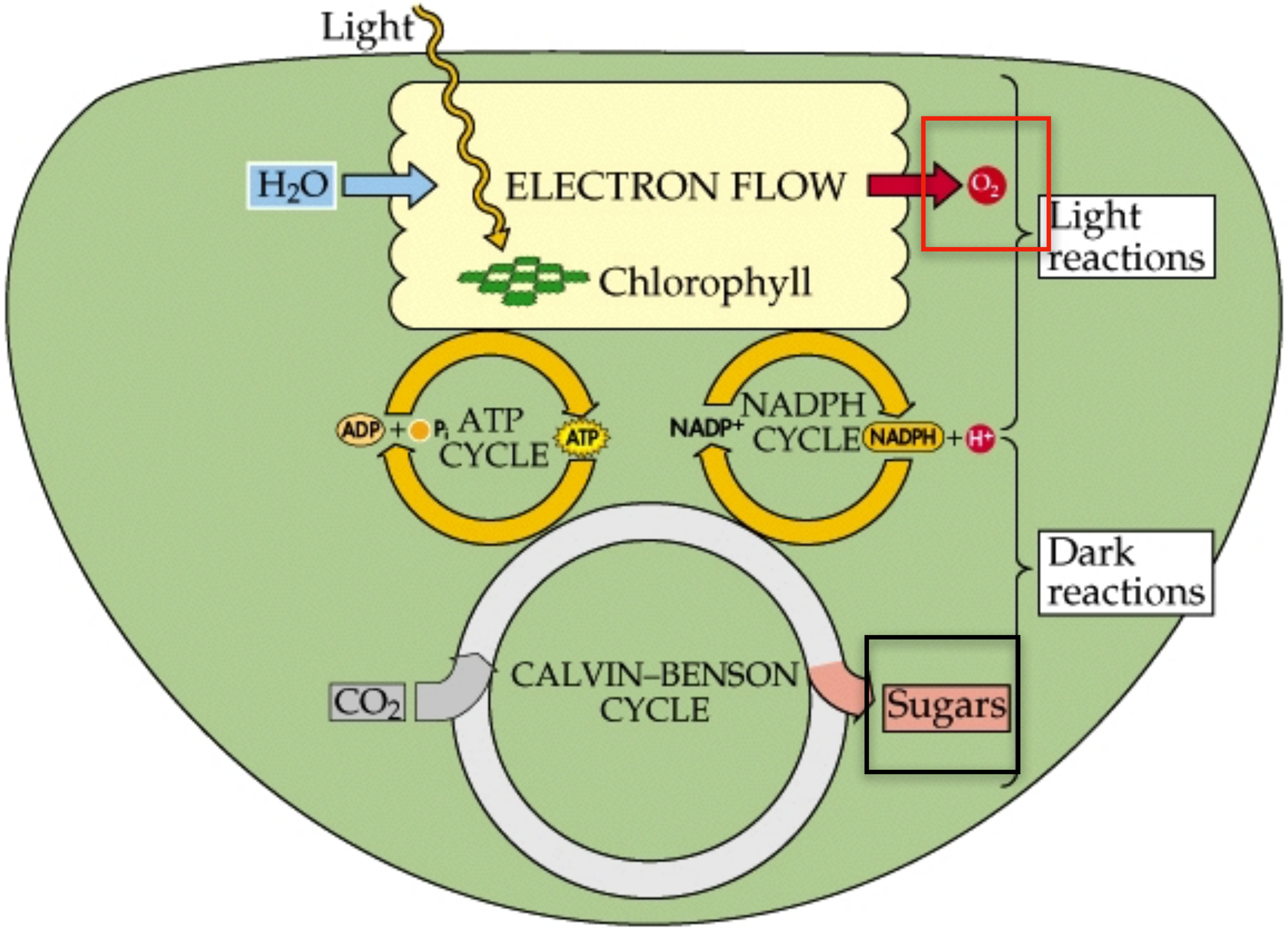


Light
H_2O
ELECTRON FLOW
O_2
Chlorophyll
Light reactions
ADP + P_i
ATP CYCLE
ATP
NADP+
NADPH CYCLE
NADPH + H+
Dark reactions
CO_2
CALVIN–BENSON CYCLE
Sugars

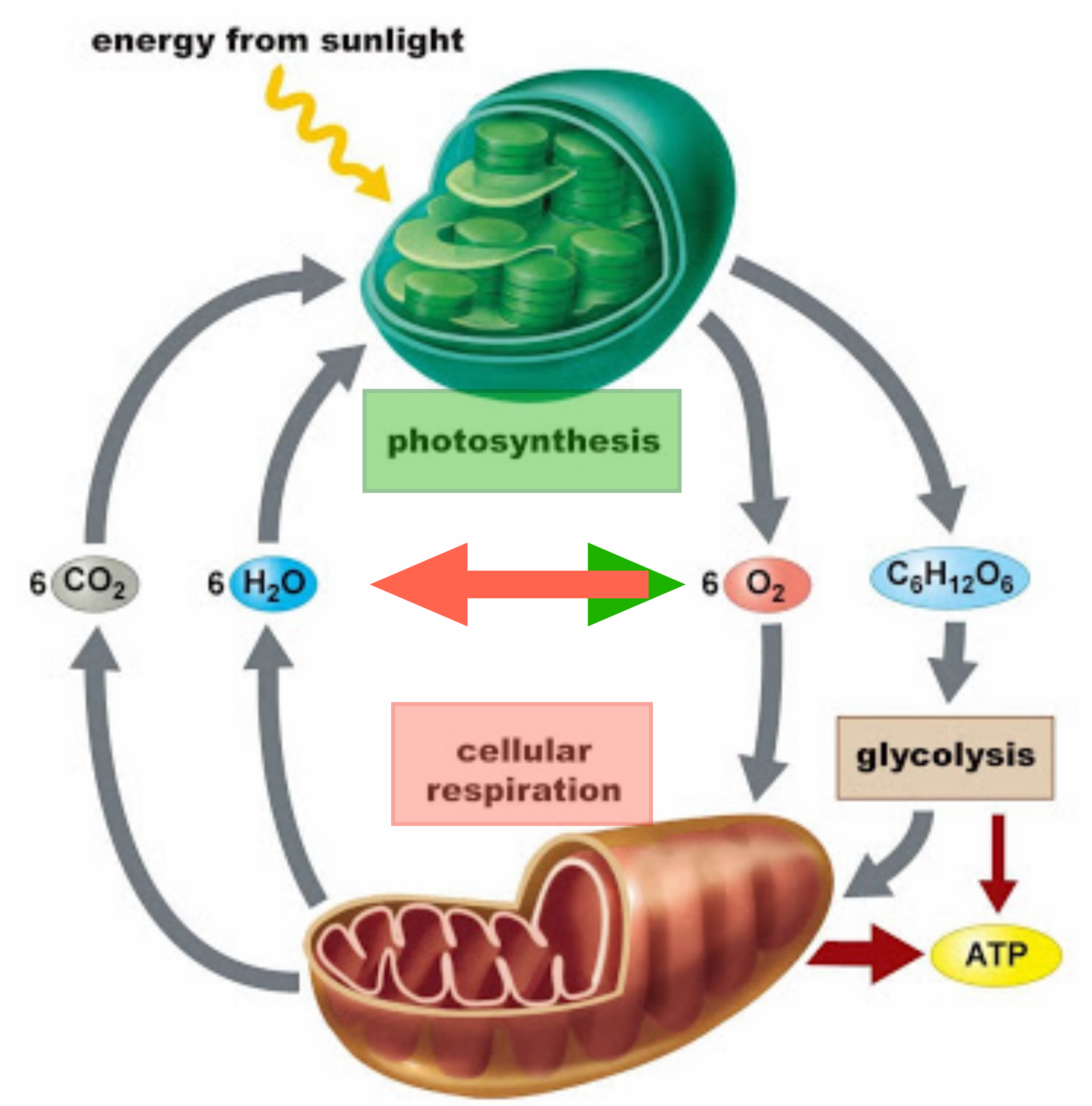


Light
H2O
ELECTRON FLOW
O2
Chlorophyll
Light reactions
ADP
Pi
ATP CYCLE
ATP
NADP+
NADPH CYCLE
NADPH
H+
Dark reactions
CO2
CALVIN–BENSON CYCLE
Sugars


Light
H_2O
ELECTRON FLOW
O_2
Chlorophyll
Light reactions
ADP + P_i
ATP CYCLE
ATP
NADP+
NADPH CYCLE
NADPH + H+
Dark reactions
CO_2
CALVIN–BENSON CYCLE
Sugars



Oxygenic photosynthesis… Plants and Cyanobacteria



Plants do BOTH