Metabolism:

Energy Release and Conservation of Energy

Metabolism

All biochemical reactions in a cell

Anabolism

Synthesizing complex molecules from simpler ones

Catabolism

Breaking complex molecules into simpler ones

Autotrophs - self feeders

Heterotrophs - other feeders

Chemoorganotrophs

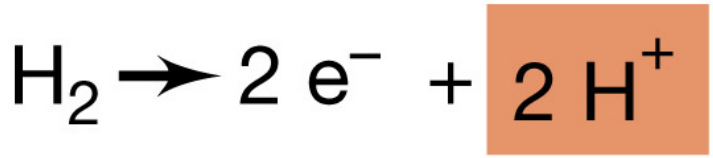
Redox Reactions

Reduction

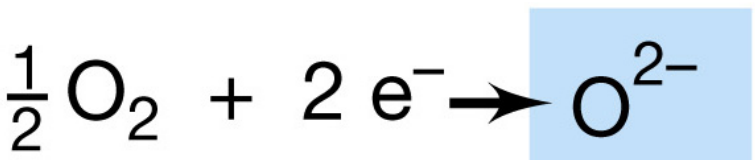
Gain of Electrons

Oxidation

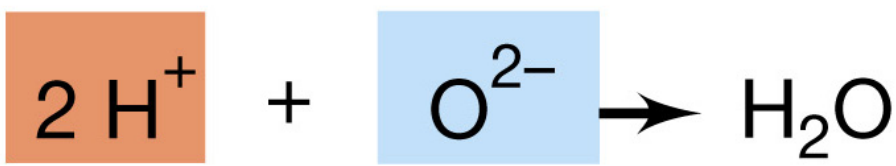
Loss of Electrons



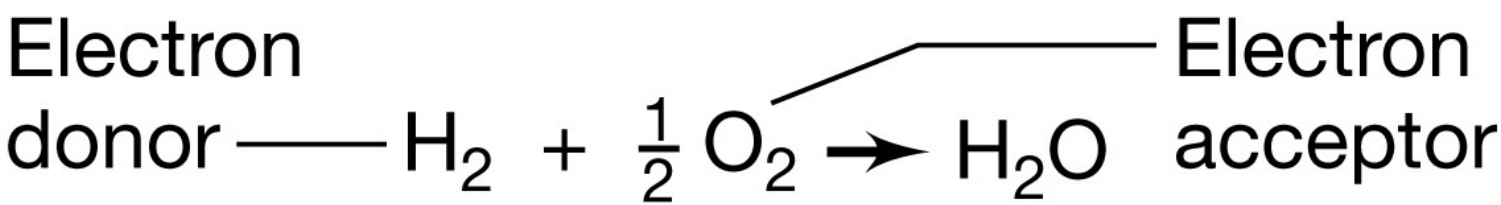
Electron-donating half reaction



Electron-accepting half reaction



Formation of water



Net reaction

Reduction Potential: E_0'

Tendency of substance to donate electrons

$1/2O_2 + 2e^- + 2\ H^+ \rightarrow H_2O$ (+0.816V)

$2e^- + 2H^+ \rightarrow H_2$ (-0.421V)

ΔE_0' ~ release of free energy

Examples of reactions with H_2 as e^- donor

(1) $H_2 + \text{fumarate}^{2-} \longrightarrow \text{succinate}^{2-}$

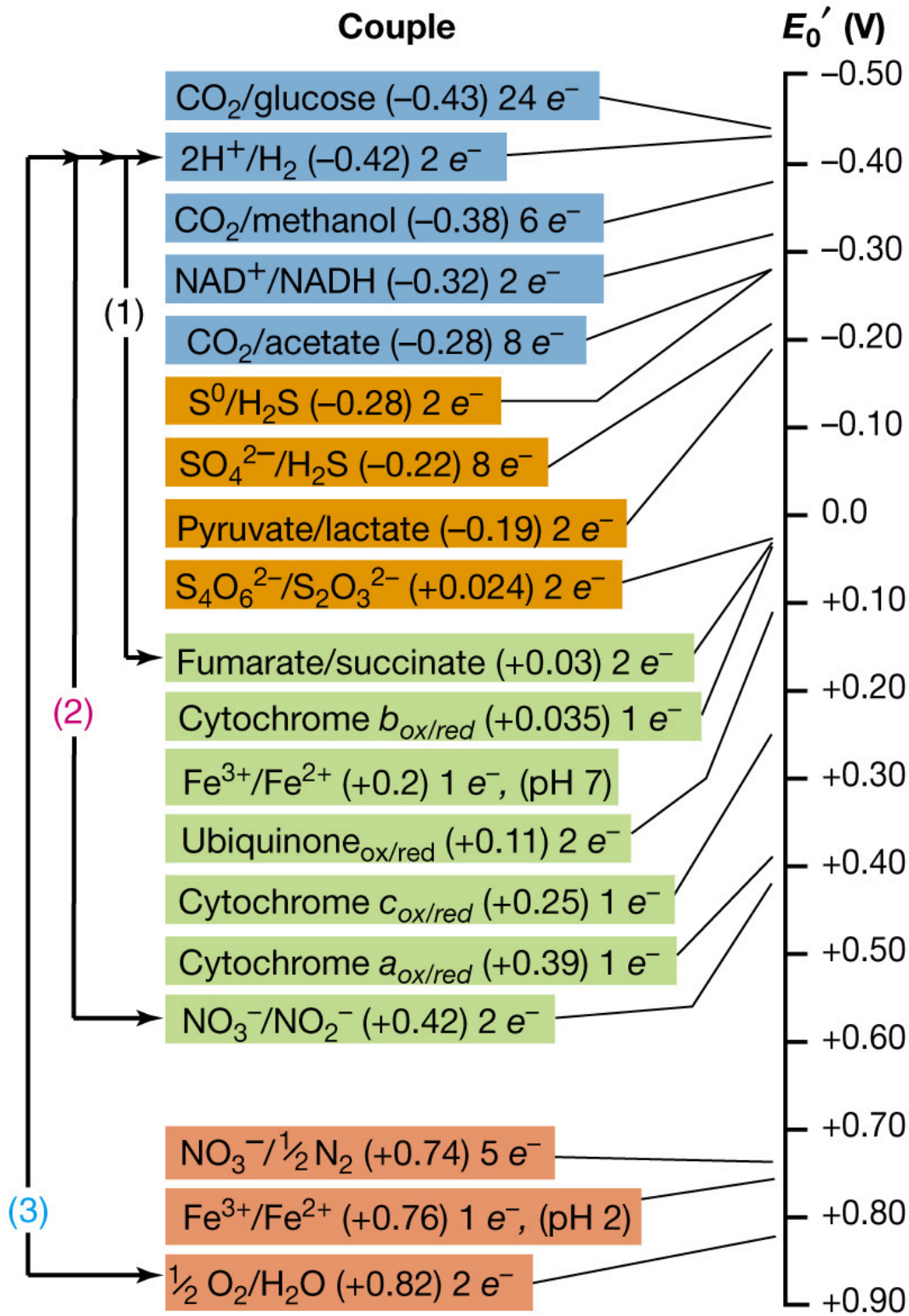
$\Delta G^{0\prime} = -86$ kJ

(2) $H_2 + NO_3^- \longrightarrow NO_2^- + H_2O$

$\Delta G^{0\prime} = -163$ kJ

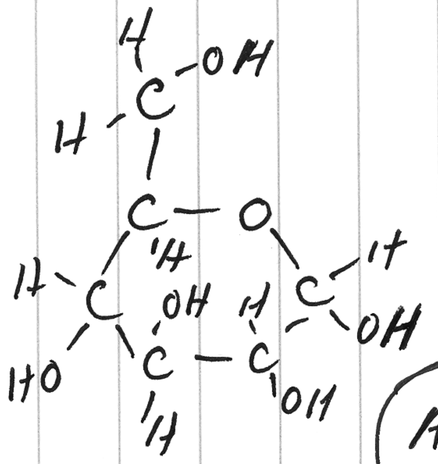
(3) $H_2 + \frac{1}{2} O_2 \longrightarrow H_2O$

$\Delta G^{0\prime} = -237$ kJ



GLYCOLYSIS

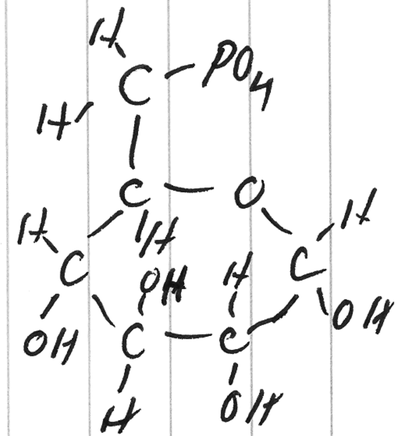
$$C_6H_{12}O_6 + 6O_2 + 38ADP + 38P_i \longrightarrow 6CO_2 + 6H_2O + 38ATP$$



GLUCOSE

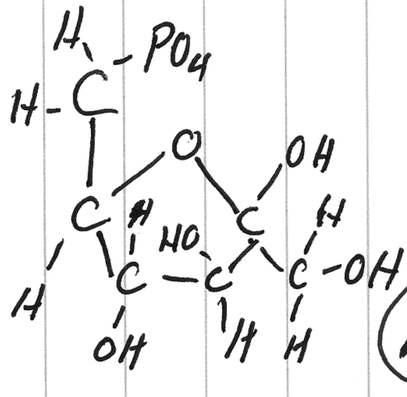
HEXOKINASE

ATP → ADP



GLUCOSE-6-PHOSPHATE

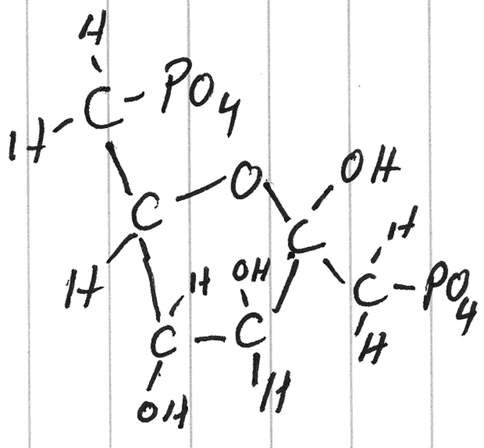
ISOMERASE



FRUCTOSE-6-PHOSPHATE

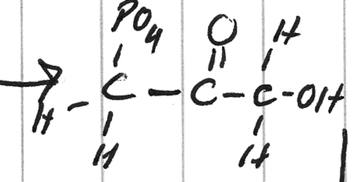
PHOSPHOFRUCTOKINASE

ATP → ADP



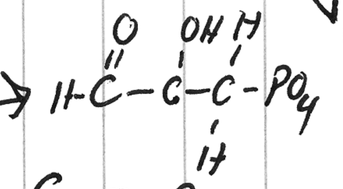
FRUCTOSE 1,6-BISPHOSPHATE

ALDOLASE



DHAP

TRIOSEPHOSPHATE ISOMERASE

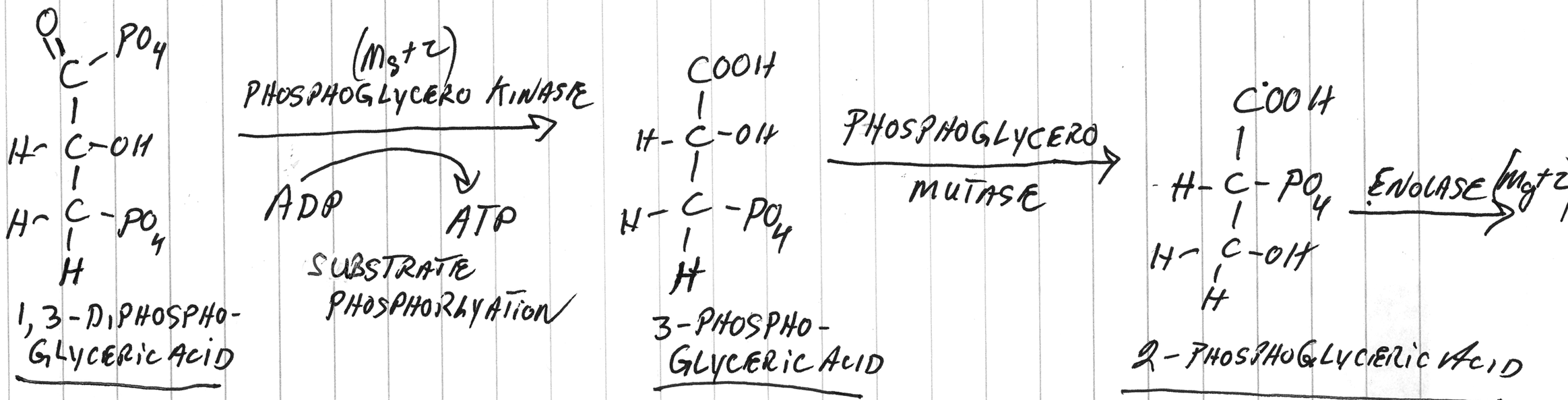


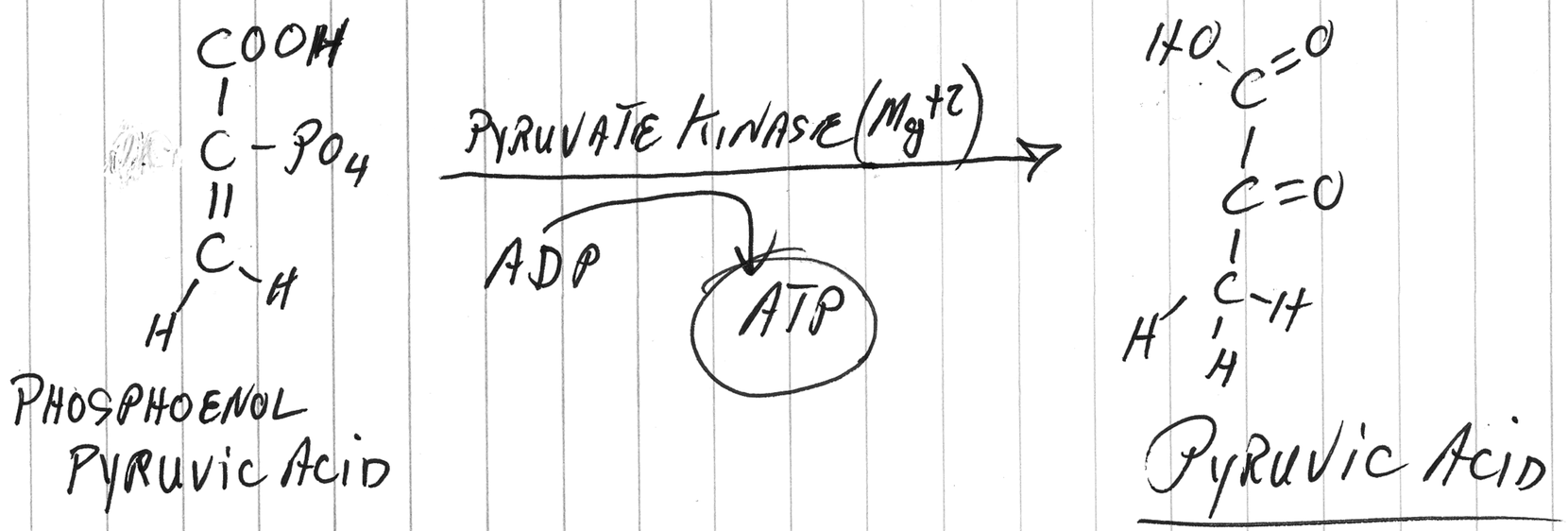
G-3-P

GLYCERALDEHYDE-3-PHOSPHATE DEHYDROGENASE

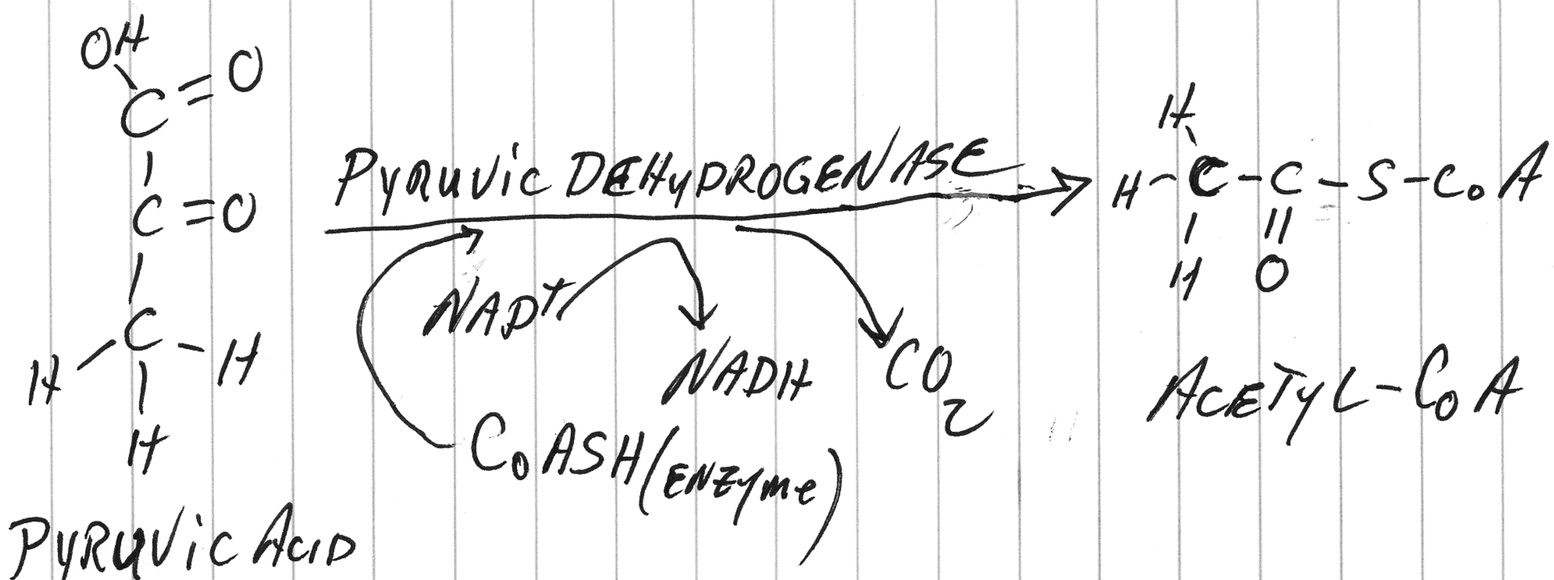
NAD^+ → NADH

P_i

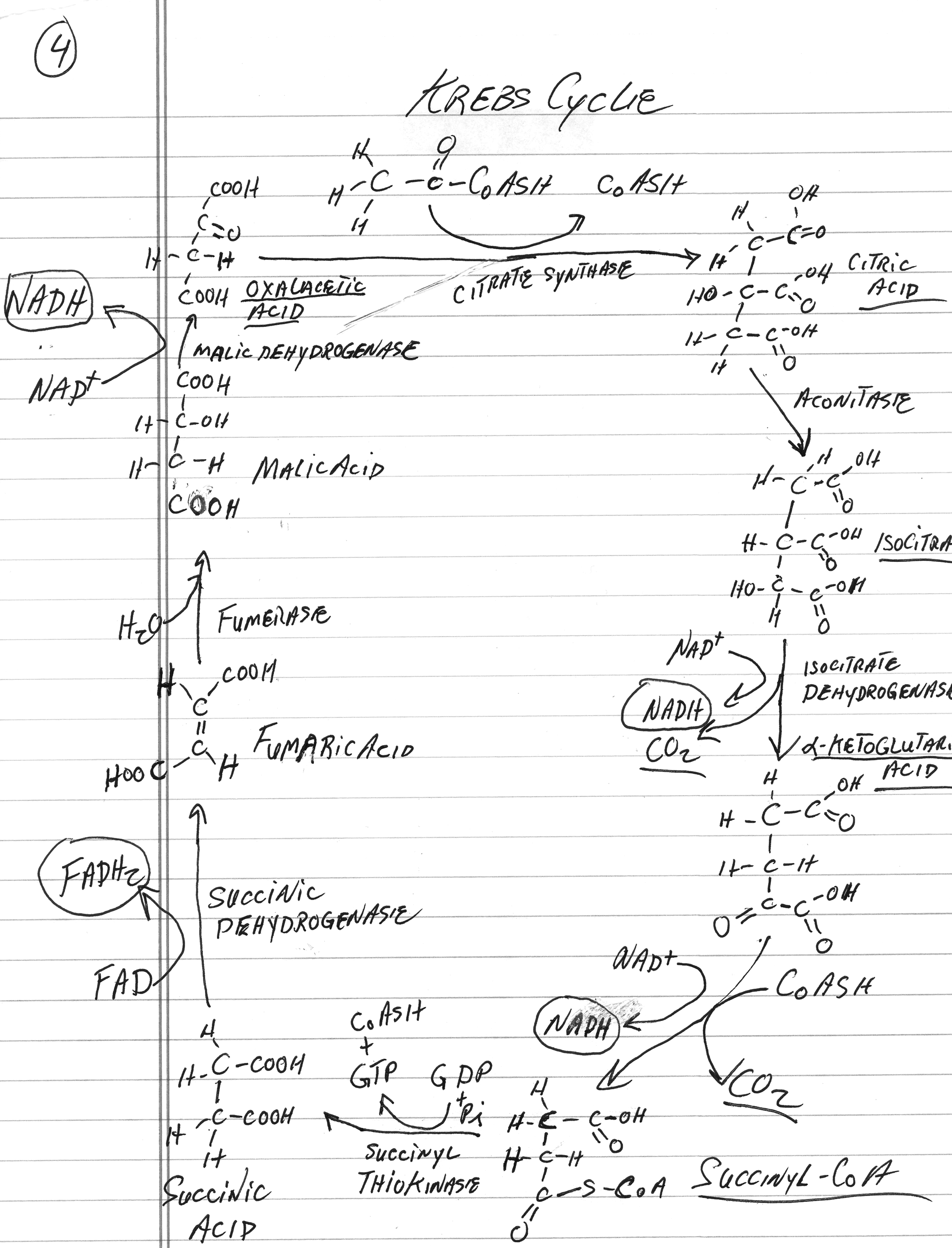

PO4
1,3-DIPHOSPHO-GLYCERIC ACID
(Mg+2)
PHOSPHOGLYCERO KINASE
ADP
ATP
SUBSTRATE PHOSPHORYLATION
COOH
3-PHOSPHO-GLYCERIC ACID
PHOSPHOGLYCERO MUTASE
2-PHOSPHOGLYCERIC ACID
ENOLASE (Mg+2)


PHOSPHOENOL PYRUVIC ACID
PYRUVATE KINASE (Mg+2)
ADP
ATP
PYRUVIC ACID

KREBS CYCLE


OH
C=O
C=O
C
H
H
H
PYRUVIC ACID
PYRUVIC DEHYDROGENASE
NAD+
NADH
CO2
CoASH (ENZYME)
H
H
C
C
S-CoA
H
O
ACETYL-CoA

KREBS Cycle

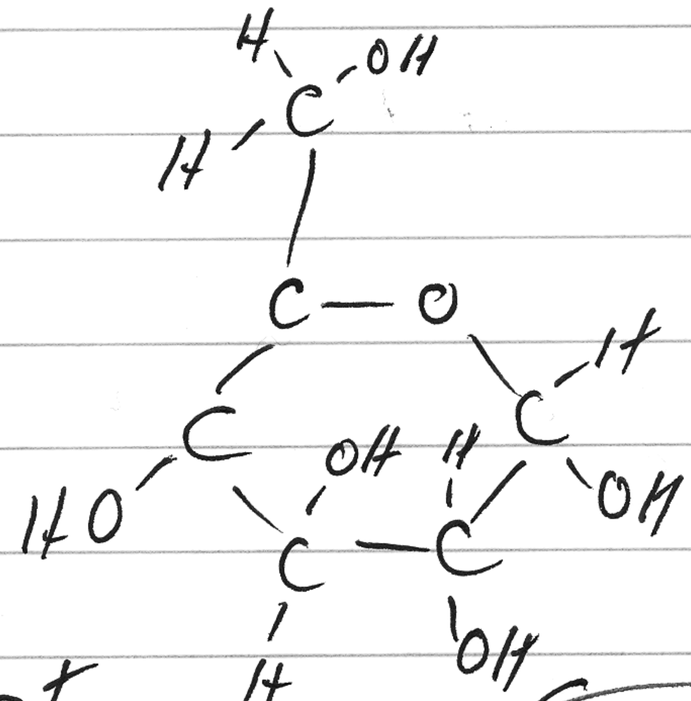

COOH
C=O
H-C-H
COOH
OXALACETIC ACID
H
H-C-C-CoASH
H
CoASH
CITRATE SYNTHASE
OH
H
C-C=O
H
HO-C-C-OH
H-C-C-OH
H
CITRIC ACID
ACONITASE
H
OH
H-C-C
O
H-C-OH
H-C-H
C-C-OH
O
O
ISOCITRATE
NAD+
NADH
CO2
ISOCITRATE DEHYDROGENASE
α-KETOGLUTARIC ACID
H
OH
H-C-C=O
H-C-H
C-C-OH
O
O
NADH
NAD+
CO2
CoASH
SUCCINYL-CoA
NAD+
NADH
MALIC DEHYDROGENASE
COOH
H-C-OH
H-C-H
COOH
MALIC ACID
H2O
FUMERASE
H
COOH
C
C
HOOC
H
FUMARIC ACID
FADH2
FAD
SUCCINIC DEHYDROGENASE
H
H-C-COOH
C-COOH
H
H
SUCCINIC ACID
CoASH + GTP
GDP + Pi
SUCCINYL THIOKINASE

(5)

FERMENTATION

RECYCLE NADH TO NAD^+

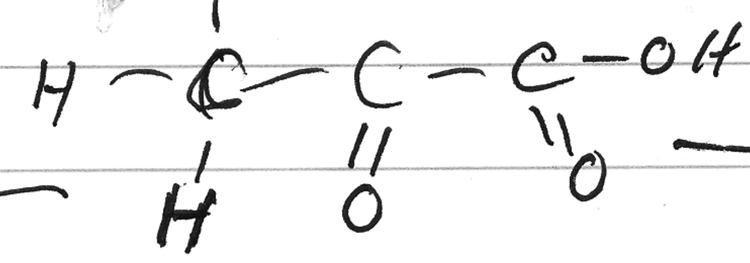
GLUCOSE



NAD^+ → NADH

GLYCOLYSIS

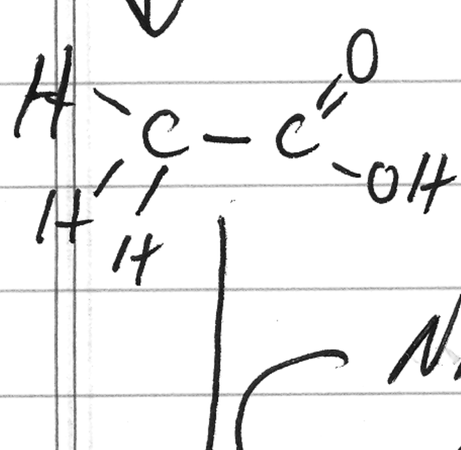
PYRUVIC ACID



NADH → NAD^+

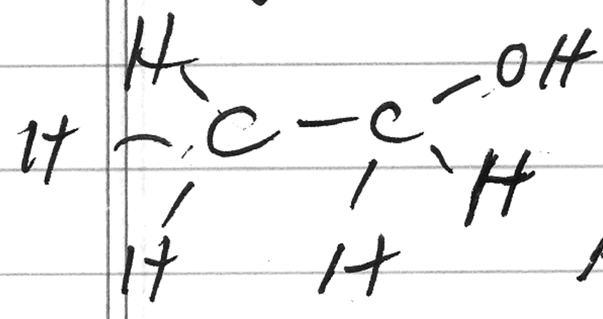
CO_2

ACETALDEHYDE



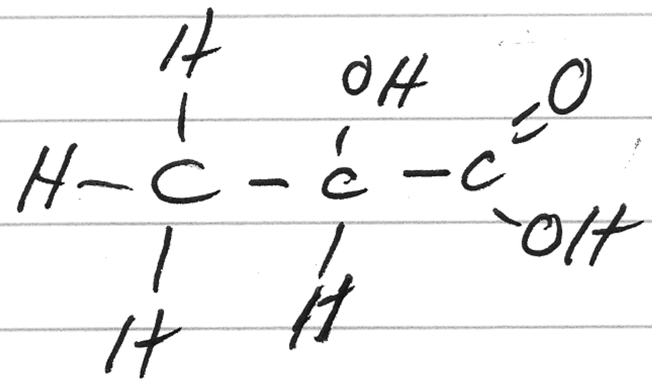
NADH → NAD^+

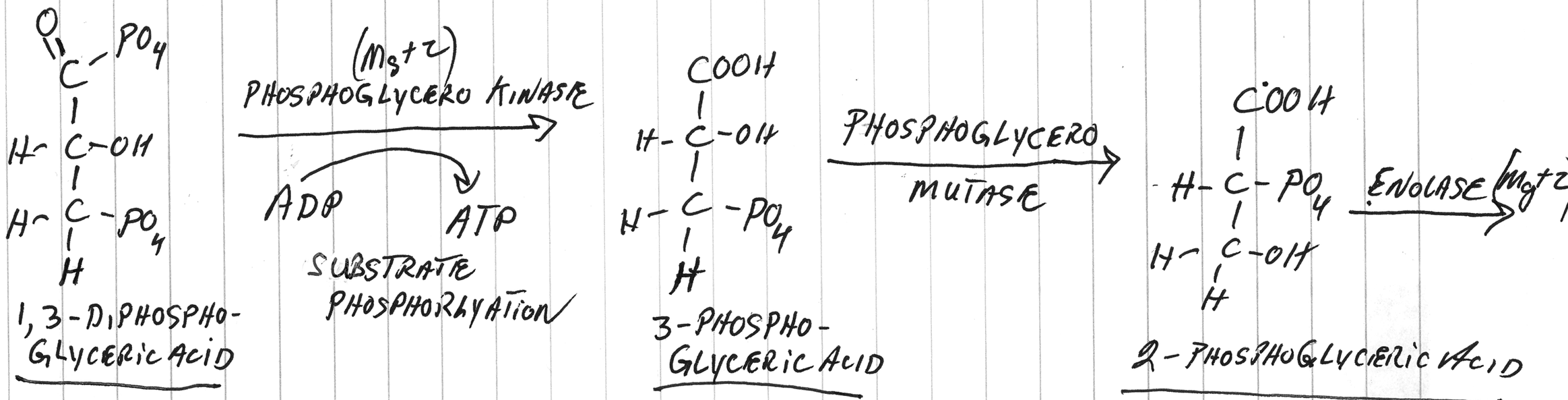
ETHYL ALCOHOL

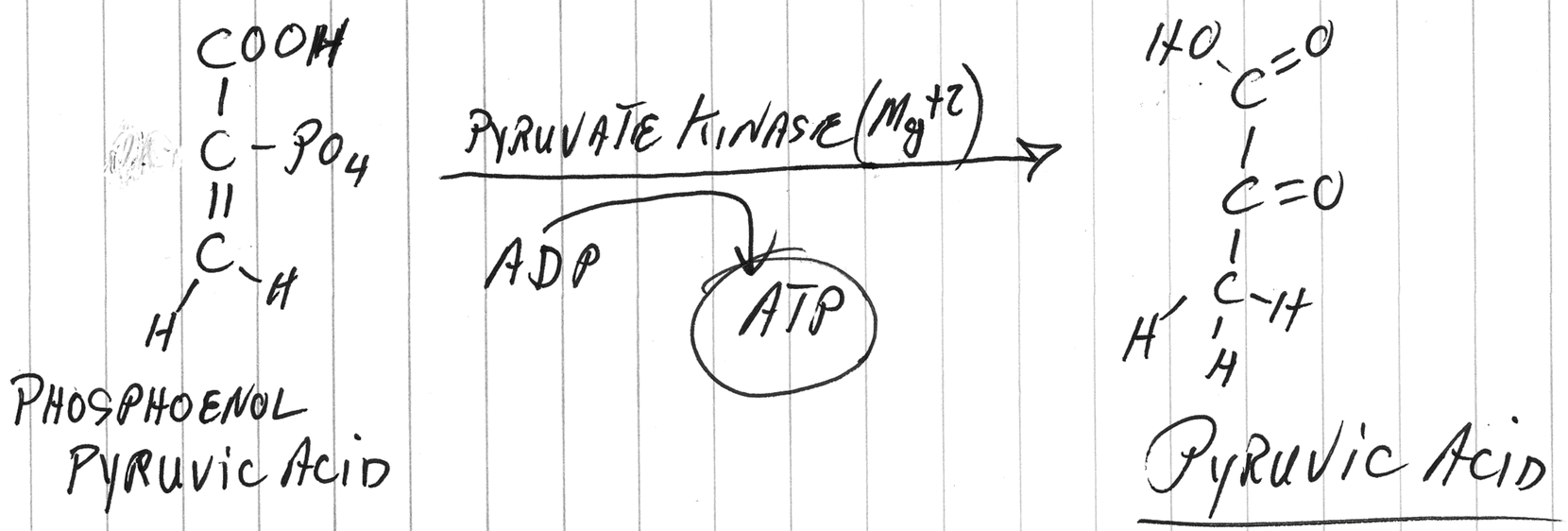


NADH → NAD^+

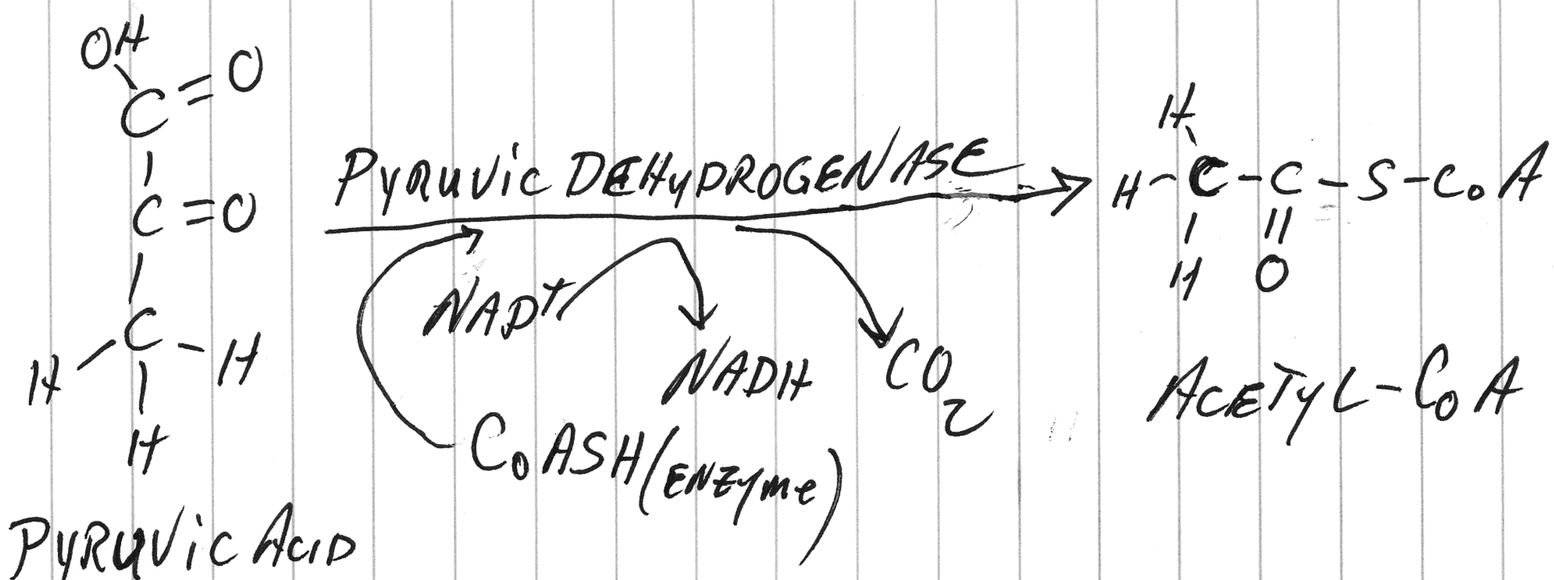
LACTIC ACID

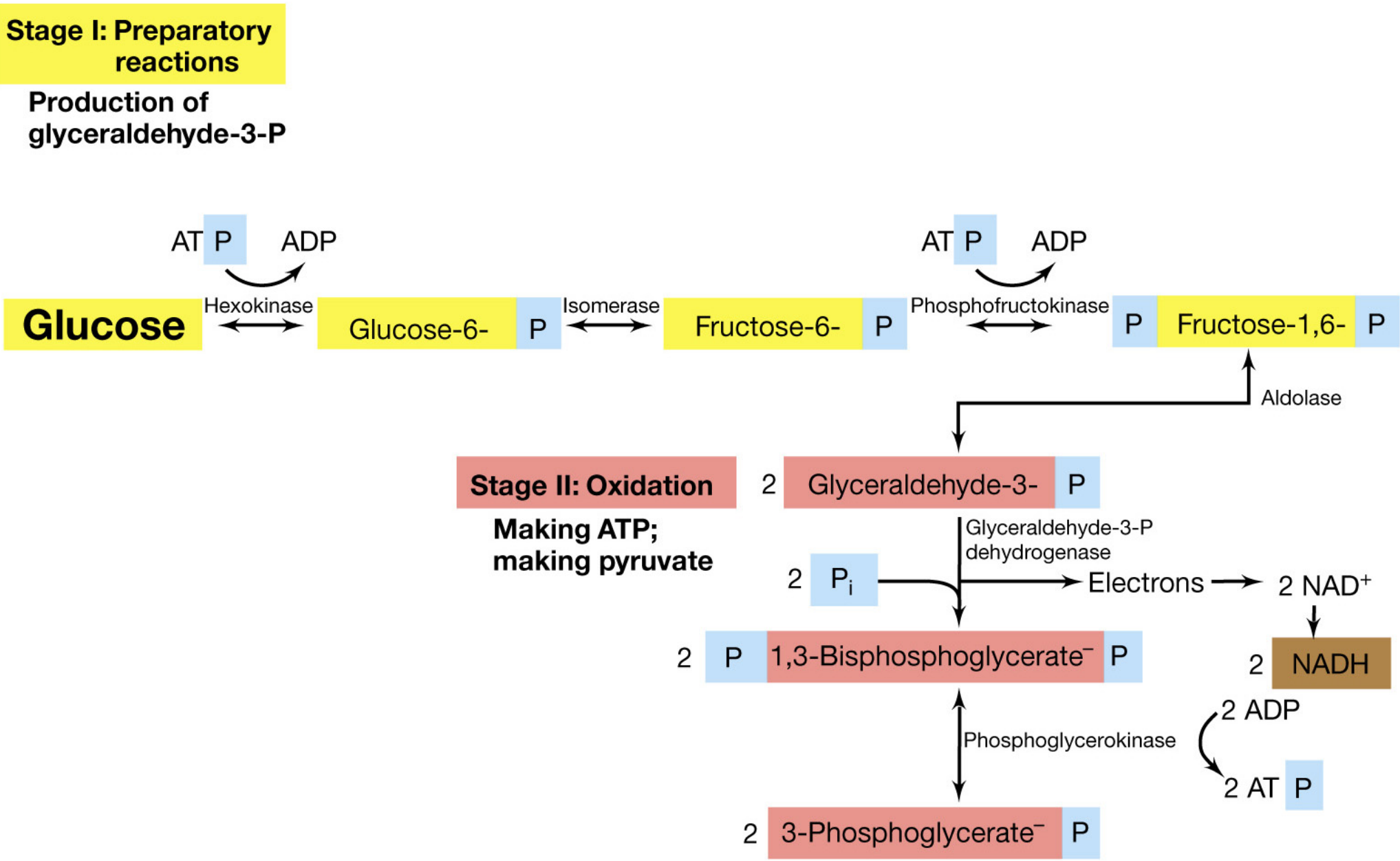


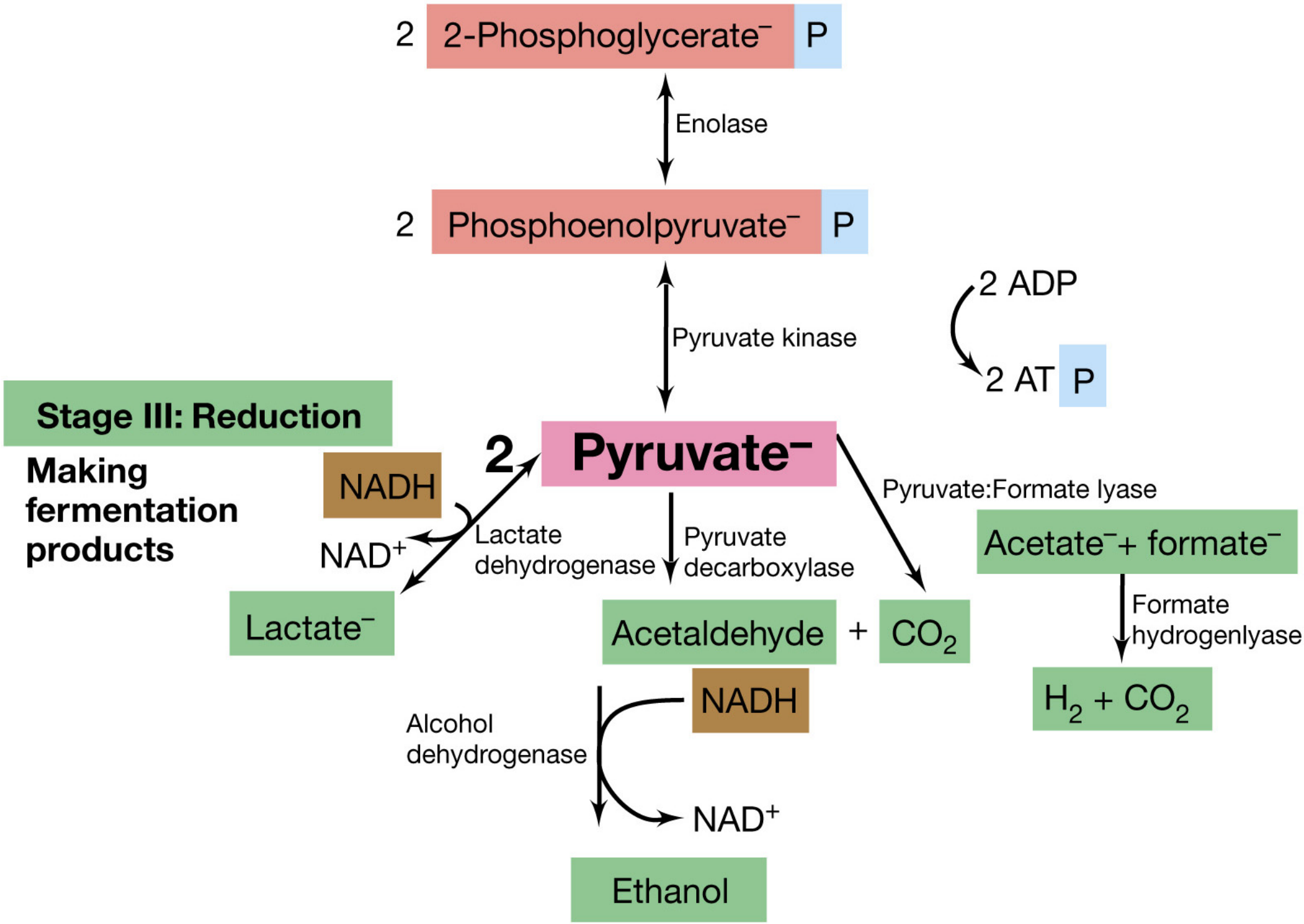

PO4
1,3-DIPHOSPHO-GLYCERIC ACID
(Mg+2)
PHOSPHOGLYCERO KINASE
ADP
ATP
SUBSTRATE PHOSPHORYLATION
COOH
3-PHOSPHO-GLYCERIC ACID
PHOSPHOGLYCERO MUTASE
2-PHOSPHOGLYCERIC ACID
ENOLASE (Mg+2)


PHOSPHOENOL PYRUVIC ACID
PYRUVATE KINASE (Mg+2)
ADP
ATP
PYRUVIC ACID

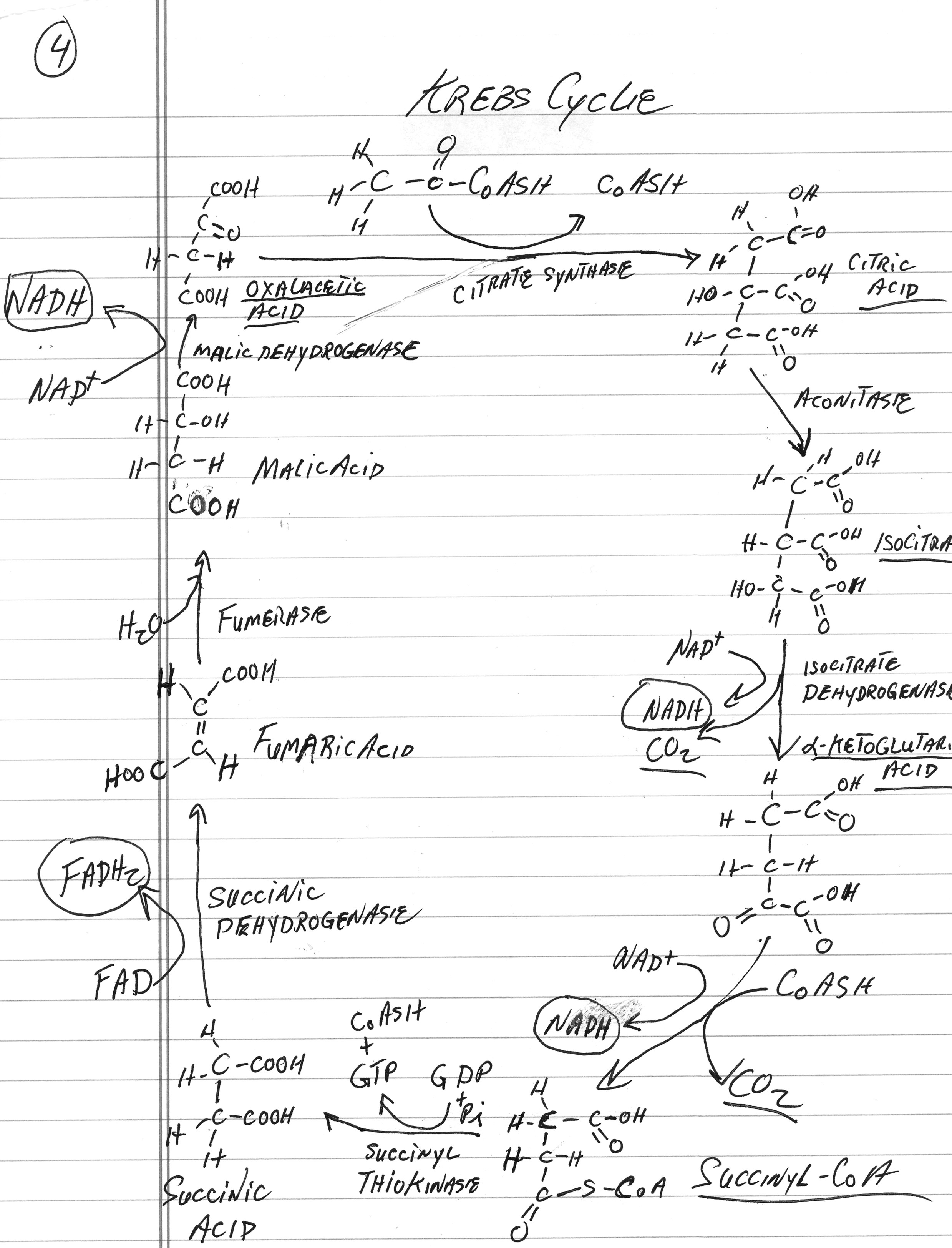
KREBS CYCLE

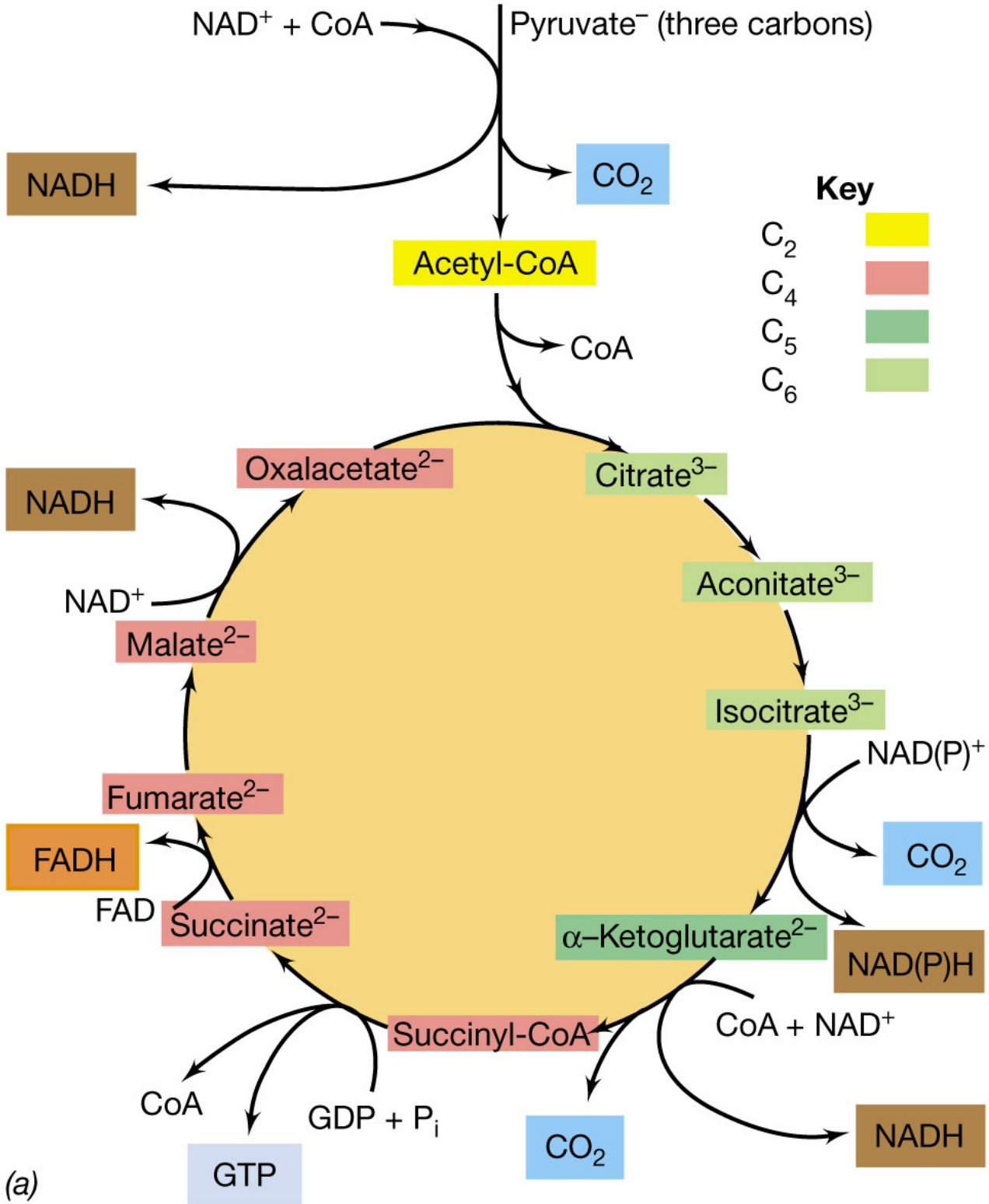

OH
C=O
C=O
C
H
H
H
PYRUVIC ACID
PYRUVIC DEHYDROGENASE
NAD+
NADH
CO2
CoASH (ENZYME)
H
H
C
C
S-CoA
H
O
ACETYL-CoA


Stage I: Preparatory reactions
Production of glyceraldehyde-3-P
ATP
ADP
Glucose
Hexokinase
Glucose-6-P
Isomerase
Fructose-6-P
ATP
ADP
Phosphofructokinase
P
Fructose-1,6-P
Aldolase
Stage II: Oxidation
Making ATP; making pyruvate
2
Glyceraldehyde-3-P
Glyceraldehyde-3-P dehydrogenase
2 P_i
Electrons
2 NAD^+
2 NADH
2 P
1,3-Bisphosphoglycerate$^-$
P
2 ADP
Phosphoglycerokinase
2 ATP
2
3-Phosphoglycerate$^-$
P


2 2-Phosphoglycerate⁻ P
Enolase
2 Phosphoenolpyruvate⁻ P
Pyruvate kinase
2 ADP
2 AT P
Stage III: Reduction
Making fermentation products
2 Pyruvate⁻
NADH
NAD+
Lactate dehydrogenase
Lactate⁻
Pyruvate decarboxylase
Acetaldehyde + CO2
Pyruvate:Formate lyase
Acetate⁻ + formate⁻
Formate hydrogenlyase
H2 + CO2
NADH
Alcohol dehydrogenase
NAD+
Ethanol

KREBS Cycle


COOH
C=O
H-C-H
COOH
OXALACETIC ACID
H
H-C-C-CoASH
H
CoASH
CITRATE SYNTHASE
OH
H
C-C=O
H
HO-C-C-OH
H-C-C-OH
H
CITRIC ACID
ACONITASE
H
OH
H-C-C
O
H-C-OH
H-C-H
C-C-OH
O
O
ISOCITRATE
NAD+
NADH
CO2
ISOCITRATE DEHYDROGENASE
α-KETOGLUTARIC ACID
H
OH
H-C-C=O
H-C-H
C-C-OH
O
O
NADH
NAD+
CO2
CoASH
SUCCINYL-CoA
NAD+
NADH
MALIC DEHYDROGENASE
COOH
H-C-OH
H-C-H
COOH
MALIC ACID
H2O
FUMERASE
H
COOH
C
C
HOOC
H
FUMARIC ACID
FADH2
FAD
SUCCINIC DEHYDROGENASE
H
H-C-COOH
C-COOH
H
H
SUCCINIC ACID
CoASH + GTP
GDP + Pi
SUCCINYL THIOKINASE

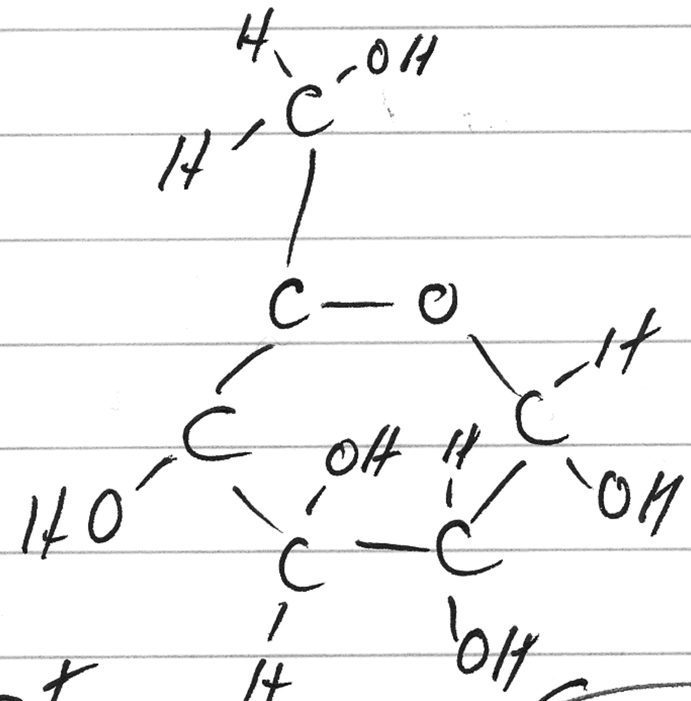

NAD+ + CoA
Pyruvate− (three carbons)
NADH
CO2
Key
C2
C4
C5
C6
Acetyl-CoA
CoA
Oxalacetate2−
Citrate3−
NADH
NAD+
Aconitate3−
Malate2−
Isocitrate3−
NAD(P)+
Fumarate2−
CO2
FADH
FAD
Succinate2−
α–Ketoglutarate2−
NAD(P)H
Succinyl-CoA
CoA + NAD+
CoA
GDP + Pi
CO2
NADH
GTP
(a)

(5)

FERMENTATION

RECYCLE NADH TO NAD^+

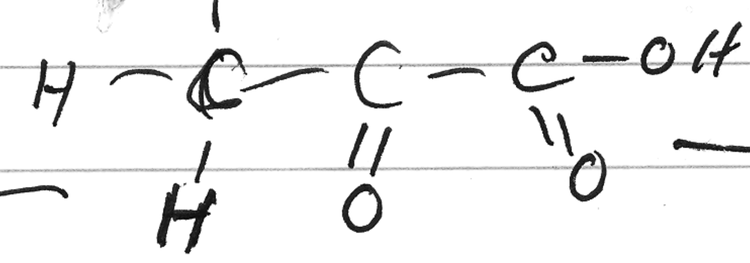
GLUCOSE



NAD^+ → NADH

GLYCOLYSIS

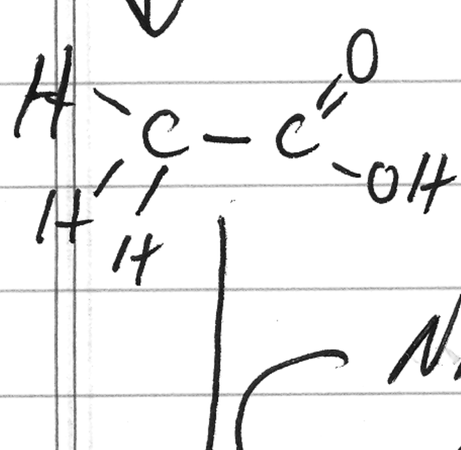
PYRUVIC ACID



NADH → NAD^+

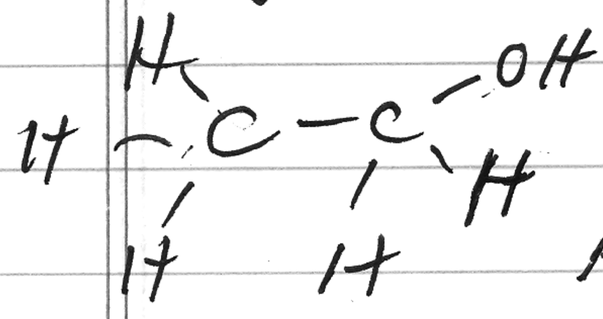
CO_2

ACETALDEHYDE



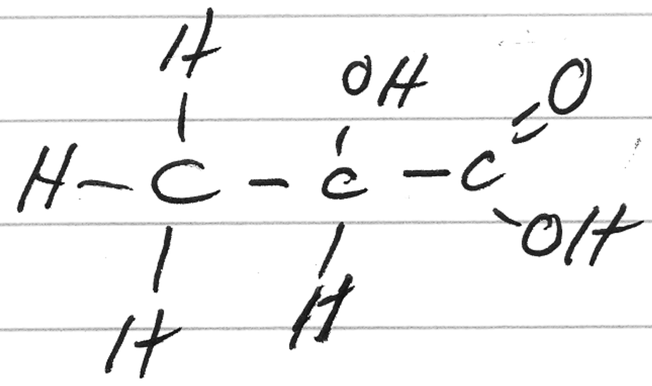
NADH → NAD^+

ETHYL ALCOHOL



NADH → NAD^+

LACTIC ACID



Fermentations

- oxidation of NADH produced by glycolysis
- pyruvate or derivative used as endogenous electron acceptor
- ATP formed by substrate-level phosphorylation

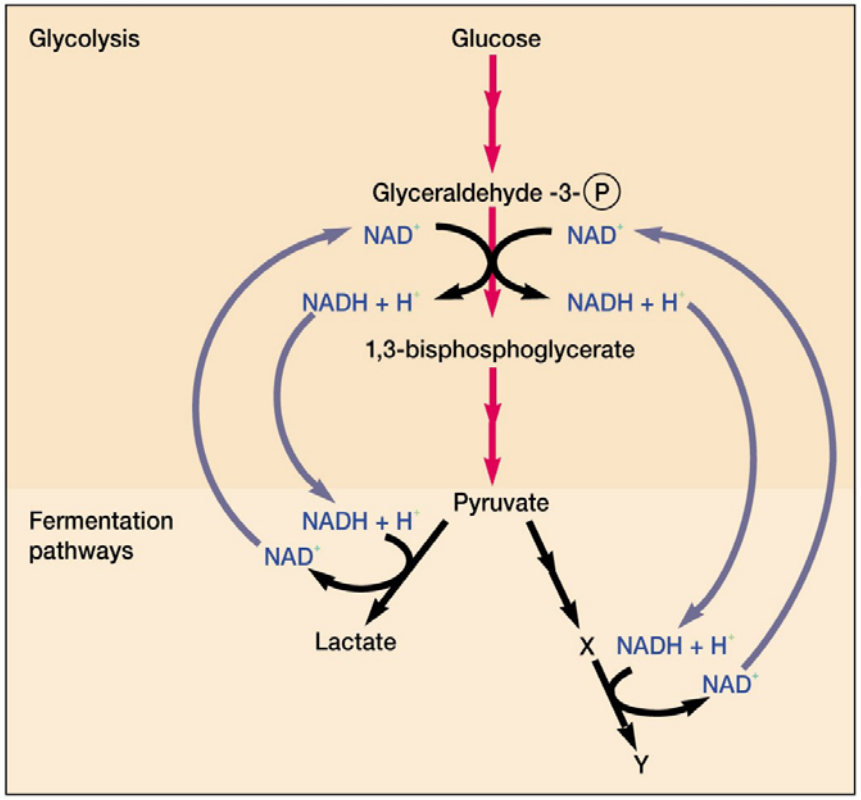


Figure 9.9

homolactic fermenters

heterolactic fermenters

food spoilage

yogurt, sauerkraut, pickles, etc.

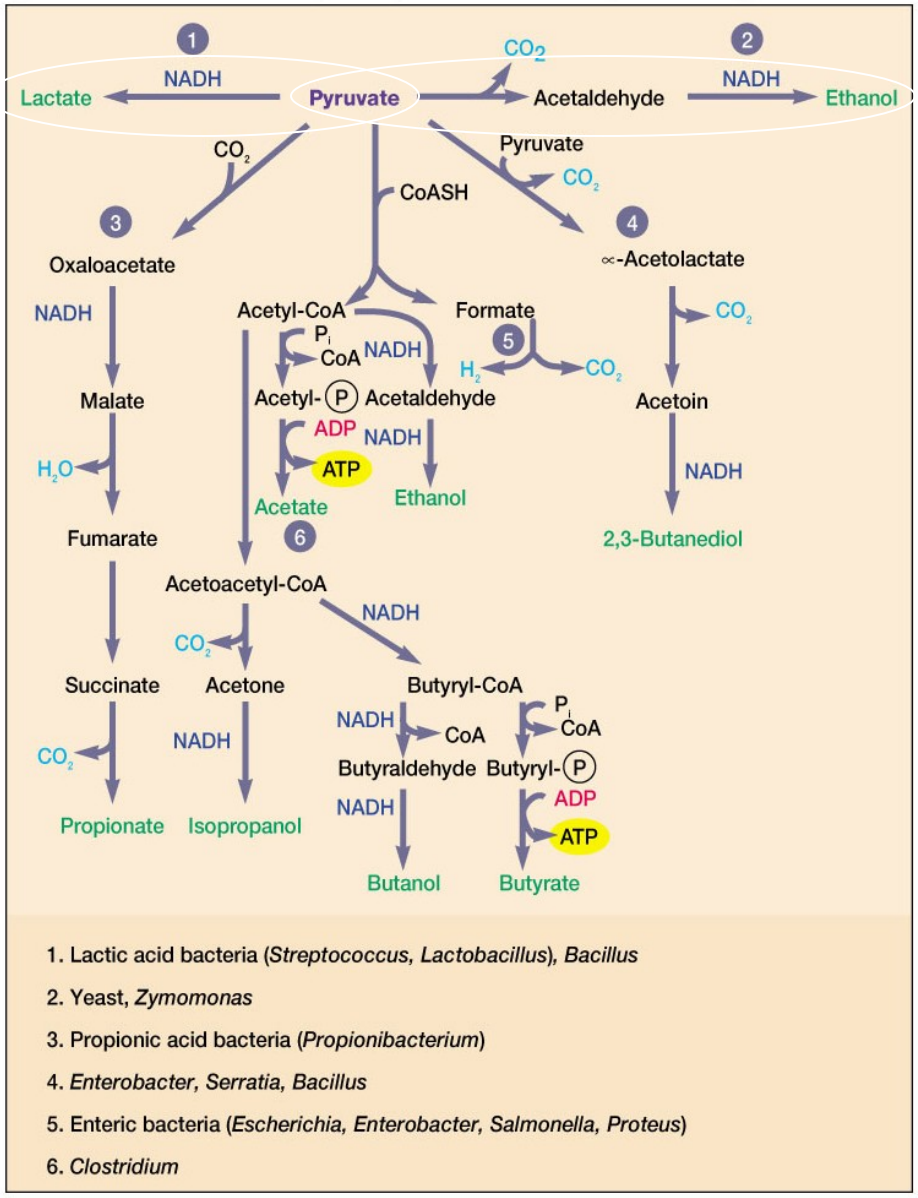
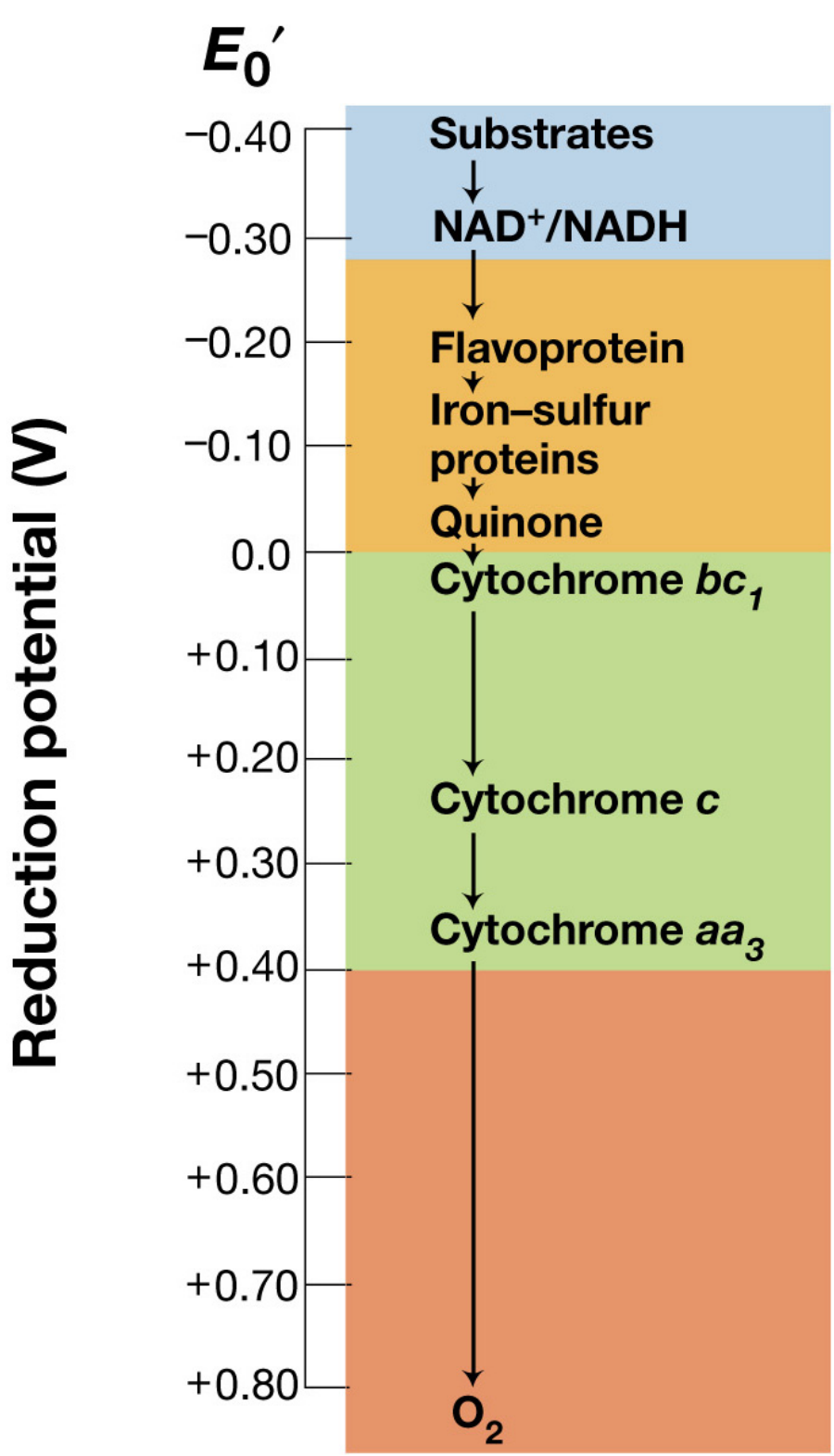


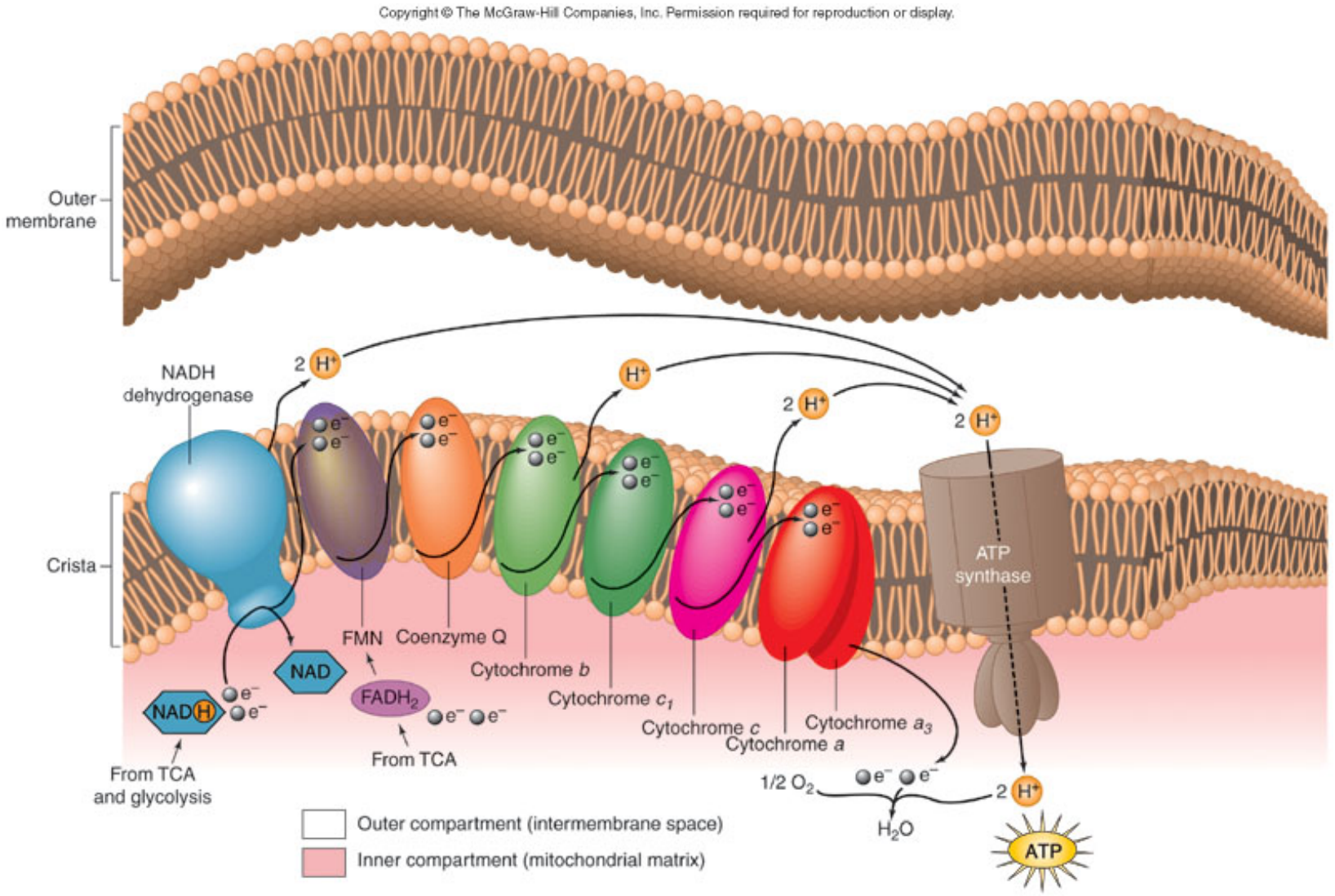
Figure 9.10

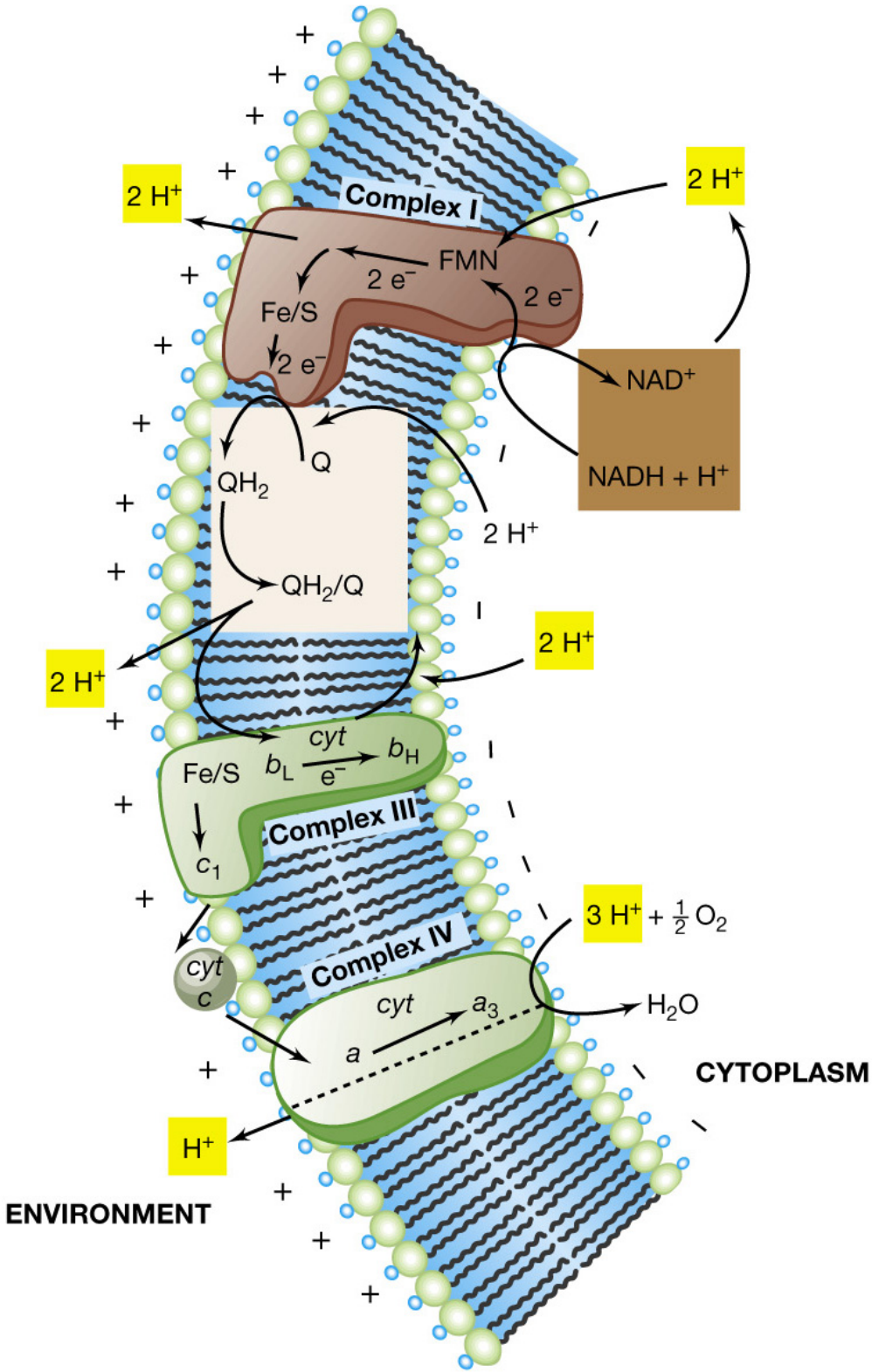
alcoholic fermentation

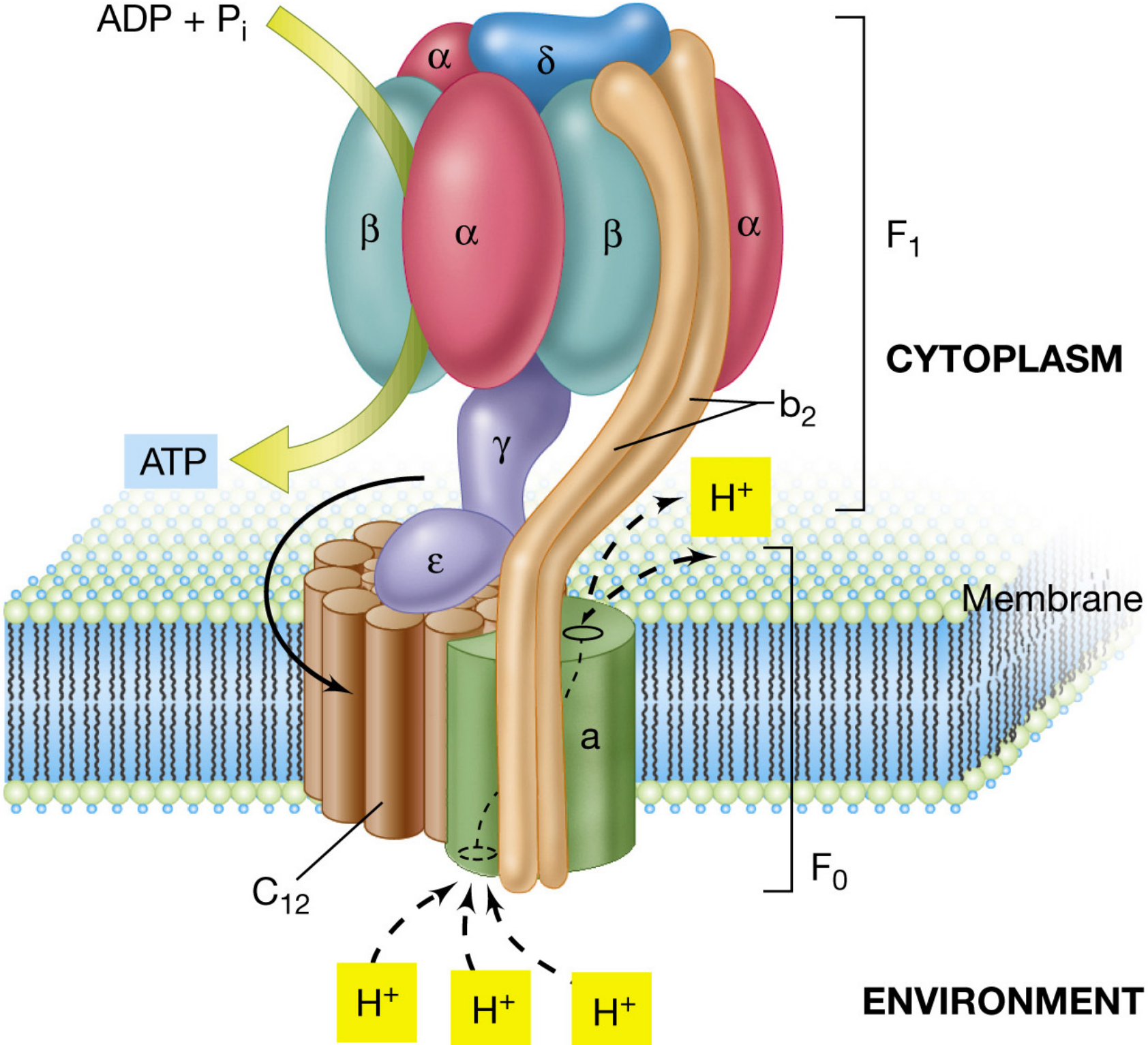
alcoholic beverages, bread, etc.

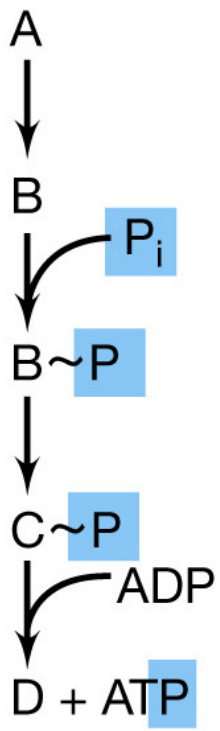

E_0'
Reduction potential (V)
−0.40
−0.30
−0.20
−0.10
0.0
+0.10
+0.20
+0.30
+0.40
+0.50
+0.60
+0.70
+0.80
Substrates
NAD+/NADH
Flavoprotein
Iron–sulfur proteins
Quinone
Cytochrome bc1
Cytochrome c
Cytochrome aa3
O2

Electron transport system

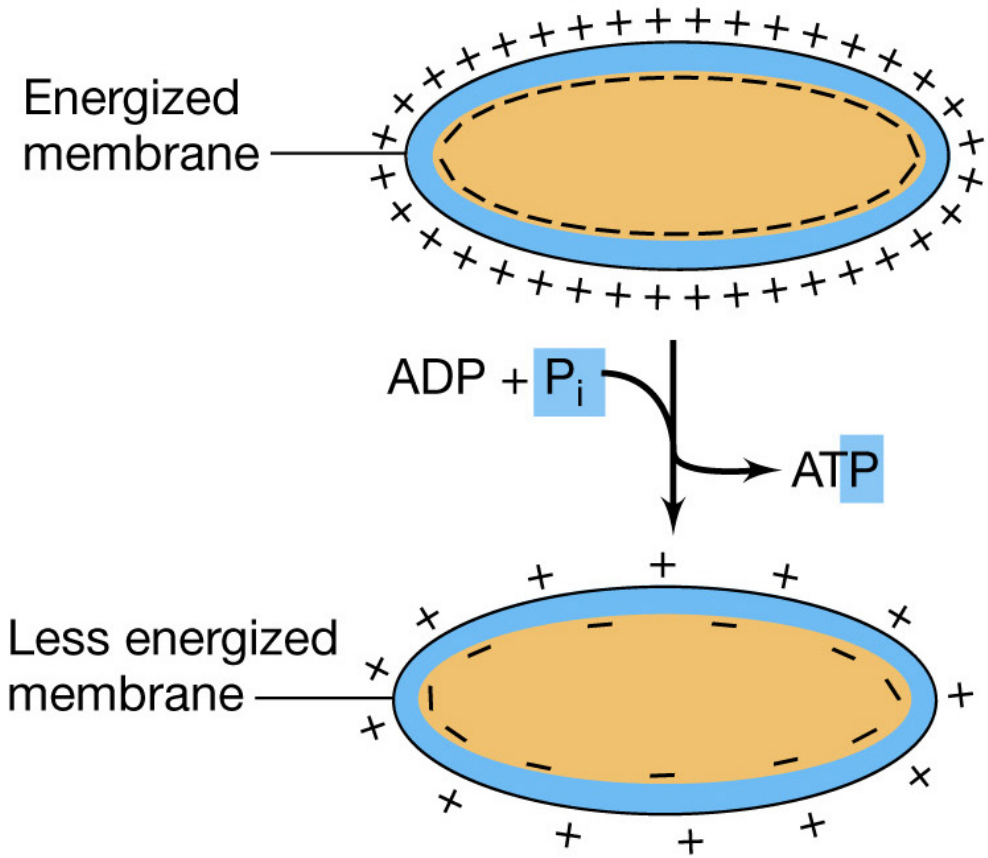



2 H+
Complex I
FMN
2 e−
Fe/S
2 e−
2 e−
2 H+
NAD+
NADH + H+
Q
QH2
QH2/Q
2 H+
2 H+
2 H+
cyt
Fe/S
bL
bH
e−
Complex III
c1
3 H+ + ½ O2
Complex IV
cyt
c
cyt
a3
a
H2O
CYTOPLASM
H+
ENVIRONMENT

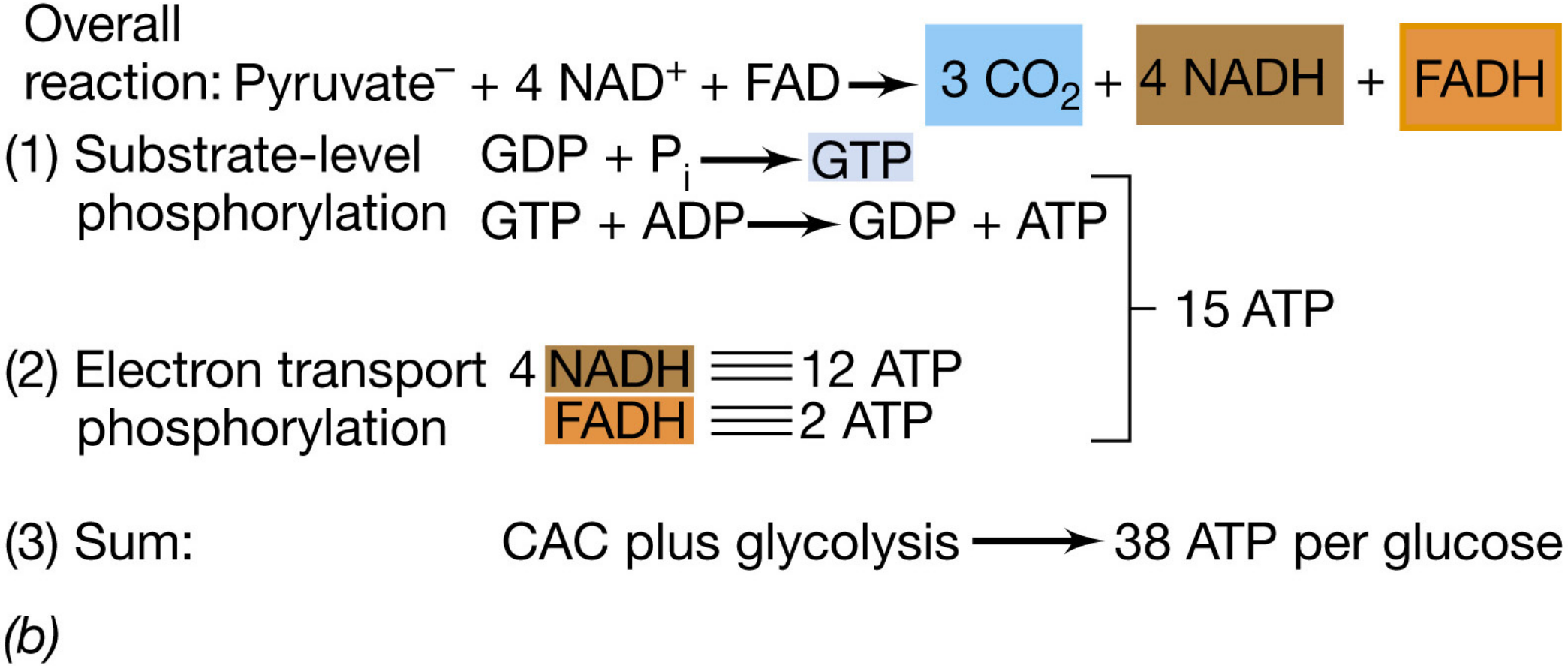

ADP + P_i
α
δ
β
α
β
α
F_1
CYTOPLASM
b_2
γ
ATP
H^+
ε
Membrane
a
C_{12}
F_0
H^+
H^+
H^+
ENVIRONMENT



(a) **Substrate-level phosphorylation**



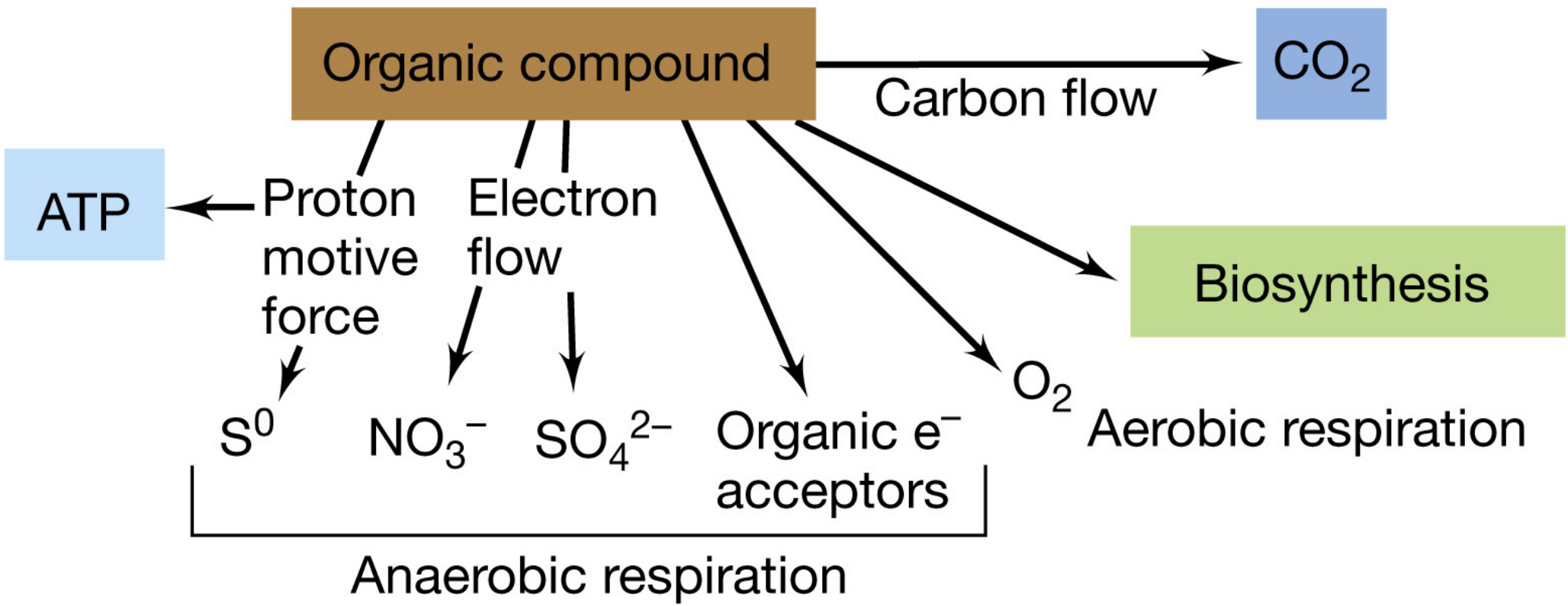
(b) **Oxidative phosphorylation**


Overall reaction: Pyruvate⁻ + 4 NAD⁺ + FAD → 3 CO2 + 4 NADH + FADH
(1) Substrate-level phosphorylation
GDP + Pi → GTP
GTP + ADP → GDP + ATP
(2) Electron transport phosphorylation
4 NADH ≡ 12 ATP
FADH ≡ 2 ATP
15 ATP
(3) Sum:
CAC plus glycolysis → 38 ATP per glucose

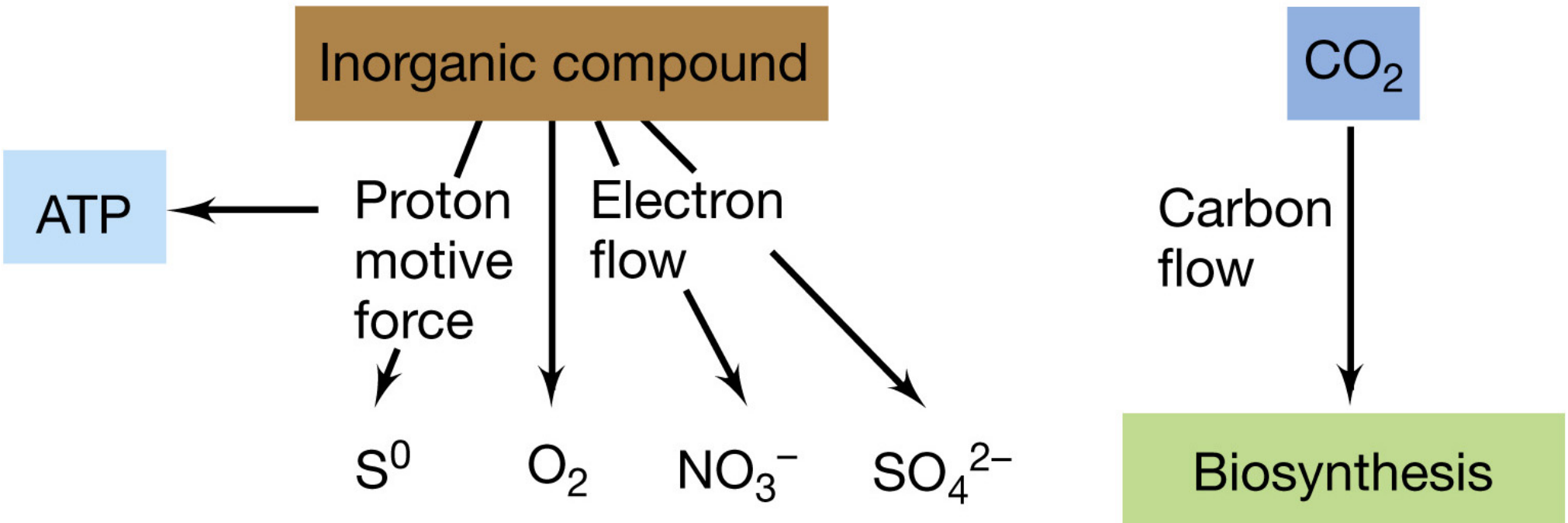
(b)

Metabolic strategies

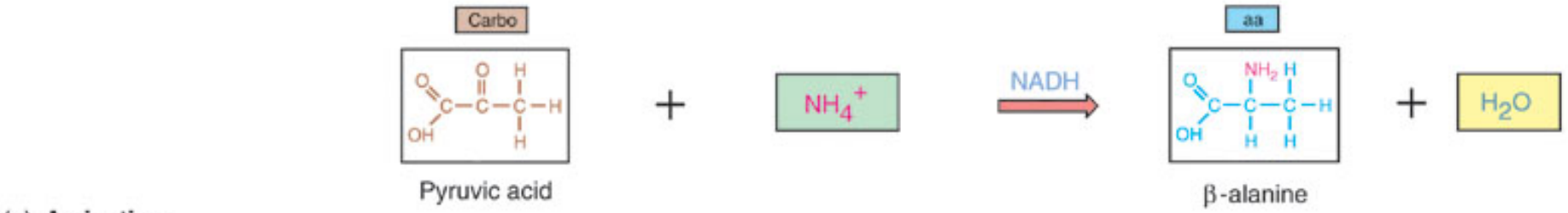
	Pathways involved	Final e-acceptor	ATP yield
Aerobic respiration	Glycolysis, TCA, ET	O_2	38
Anaerobic respiration	Glycolysis, TCA, ET	NO_3^-, SO_4^{-2}, CO_3^{-3}	Variable 34 – 36
Fermentation	Glycolysis	Organic molecules	2



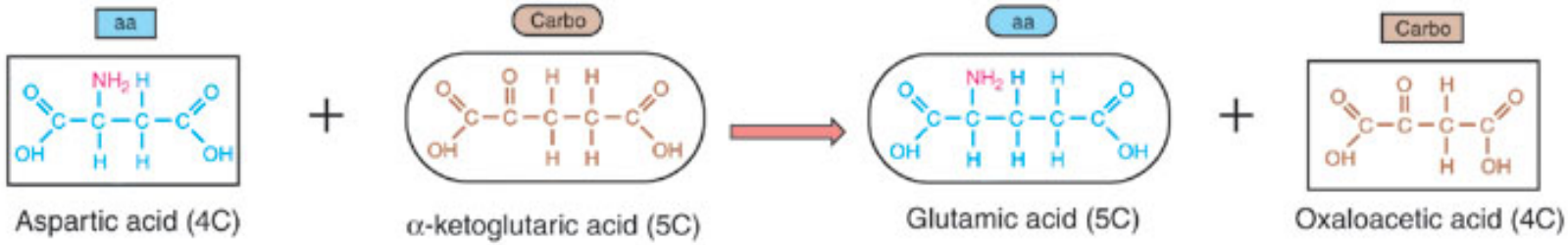
(a) **Chemoorganotrophic metabolism**



(b) **Chemolithotrophic metabolism**



(a) **Amination**



(b) **Transamination**

(c) **Deamination**