Metabolic charts

Explanations

The following 13 plates (pp. 407–419) provide a concise schematic overview of the most important metabolic pathways. Explanatory text is deliberately omitted from them.

These "charts":

- Contain details of metabolic pathways that are only shown in outline in the main text for reasons of space. This applies in particular to the synthesis and degradation of the amino acids and nucleotides, and for some aspects of carbohydrate and lipid metabolism.
- Offer a quick overview of a specific pathway, the metabolites that arise in it, and the enzymes involved.
- Can be used for reference purposes and for revising material previously learned.

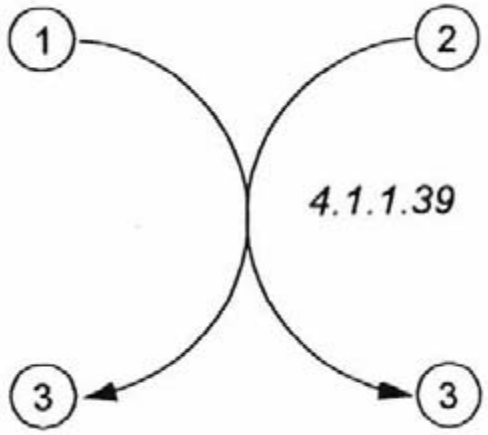
The most important **intermediates** are shown with numbers in the charts. The corresponding compounds can be identified using the table on the same page.

In addition, at each step the four-figure EC number (see p. 88) for the **enzyme** responsible for a reaction is given in *italics*. The enzyme name and its systematic classification in the system used by the *Enzyme Catalogue* are available in the following **annotated enzyme list** (pp. 420–430), in which all of the enzymes mentioned in this book are listed according to their EC number. The book's index is helpful when looking for a specific enzyme in the text.

In reactions that involve **coenzymes**, the coenzyme names are also given (sometimes in simplified form). Particularly important starting, intermediate, or end products are given with the full name, or as formulae.

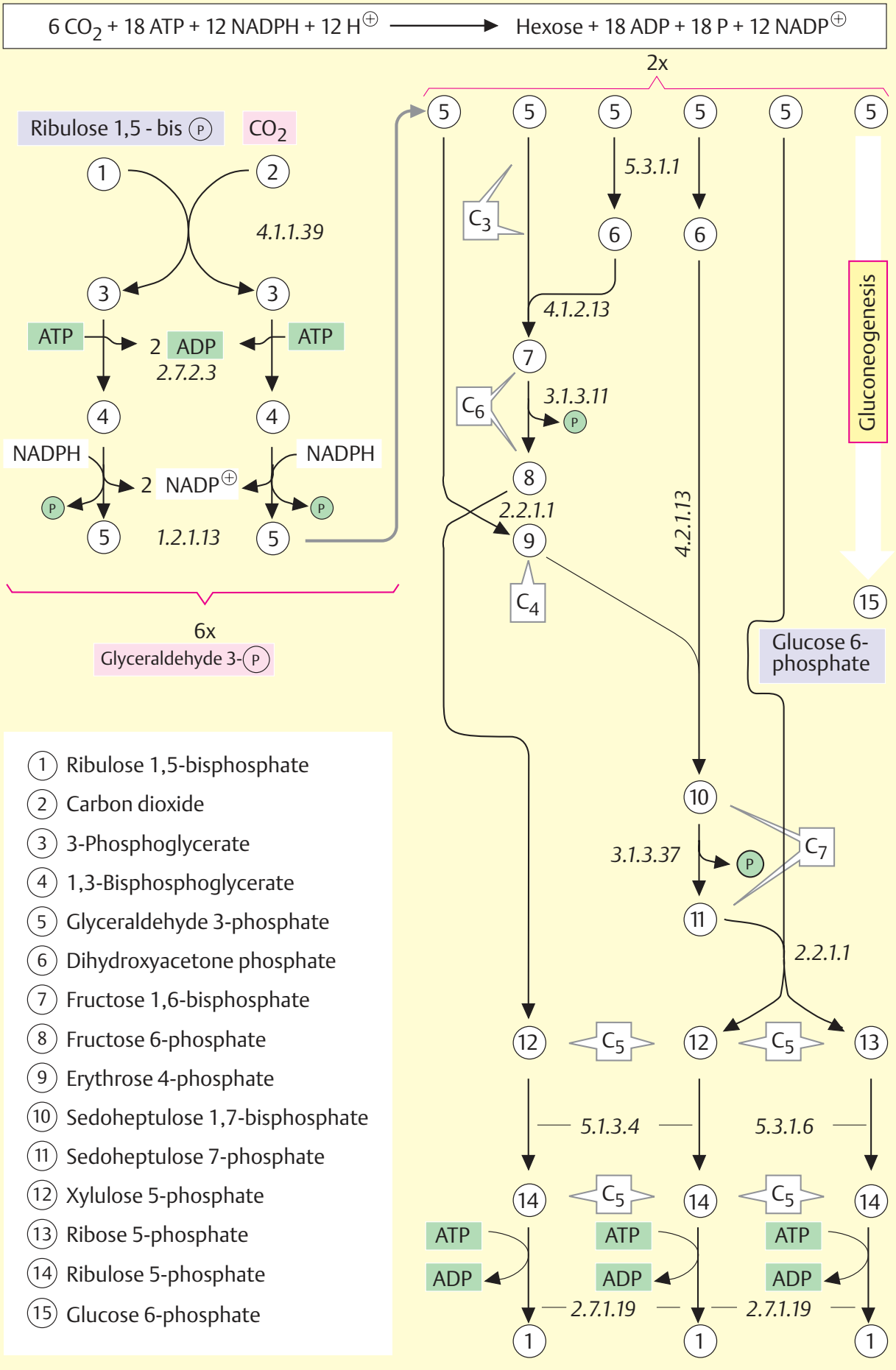
Example

On p. 407, the initial step of the dark reactions in plant photosynthesis (in the Calvin cycle) is shown at the top left.

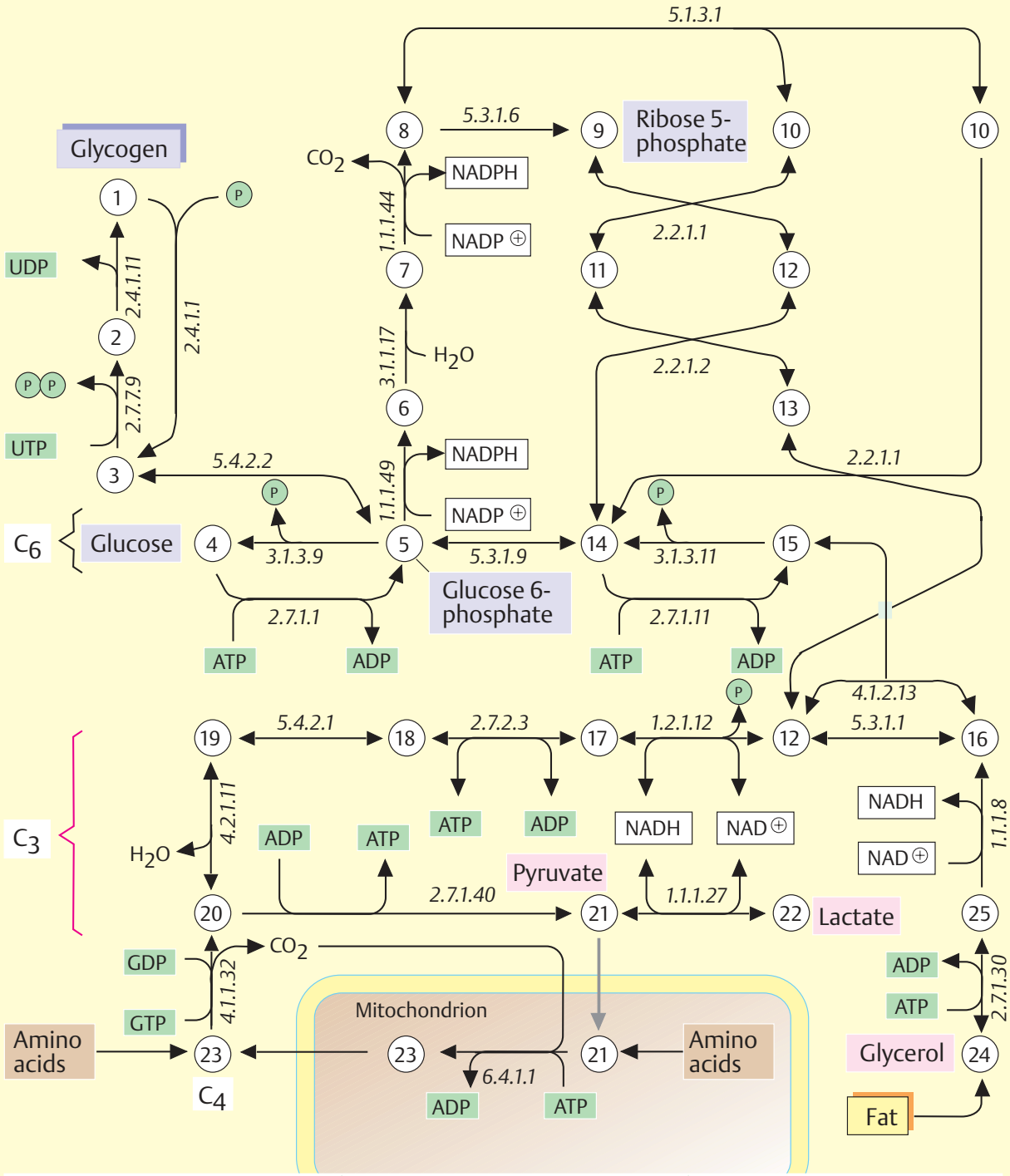


In this reaction, one molecule of ribulose-1,5-bisphosphate (metabolite 1) and one molecule of CO_2 (metabolite 2) give rise to two molecules of 3-phosphoglycerate (metabolite 3). The enzyme responsible has the EC number *4.1.1.39*. The annotated enzyme list shows that this refers to *ribulose bisphosphate carboxylase* ("rubisco" for short). Rubisco belongs to enzyme class 4 (the lyases) and, within that group, to subclass 4.1 (the carboxy-lyases). It contains copper as a cofactor ([Cu]).

A. Calvin cycle (plant chloroplasts)

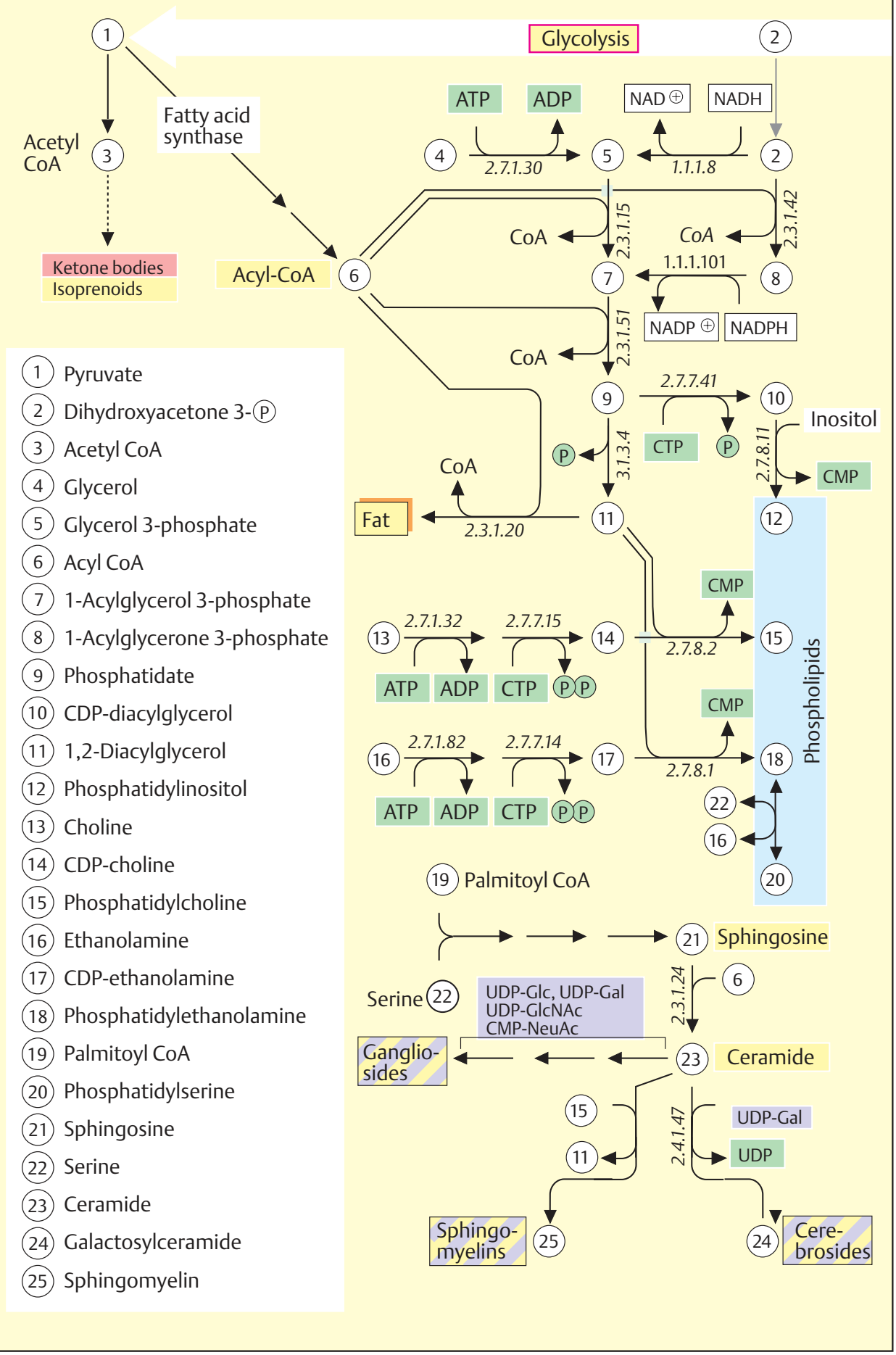


A. Carbohydrate metabolism



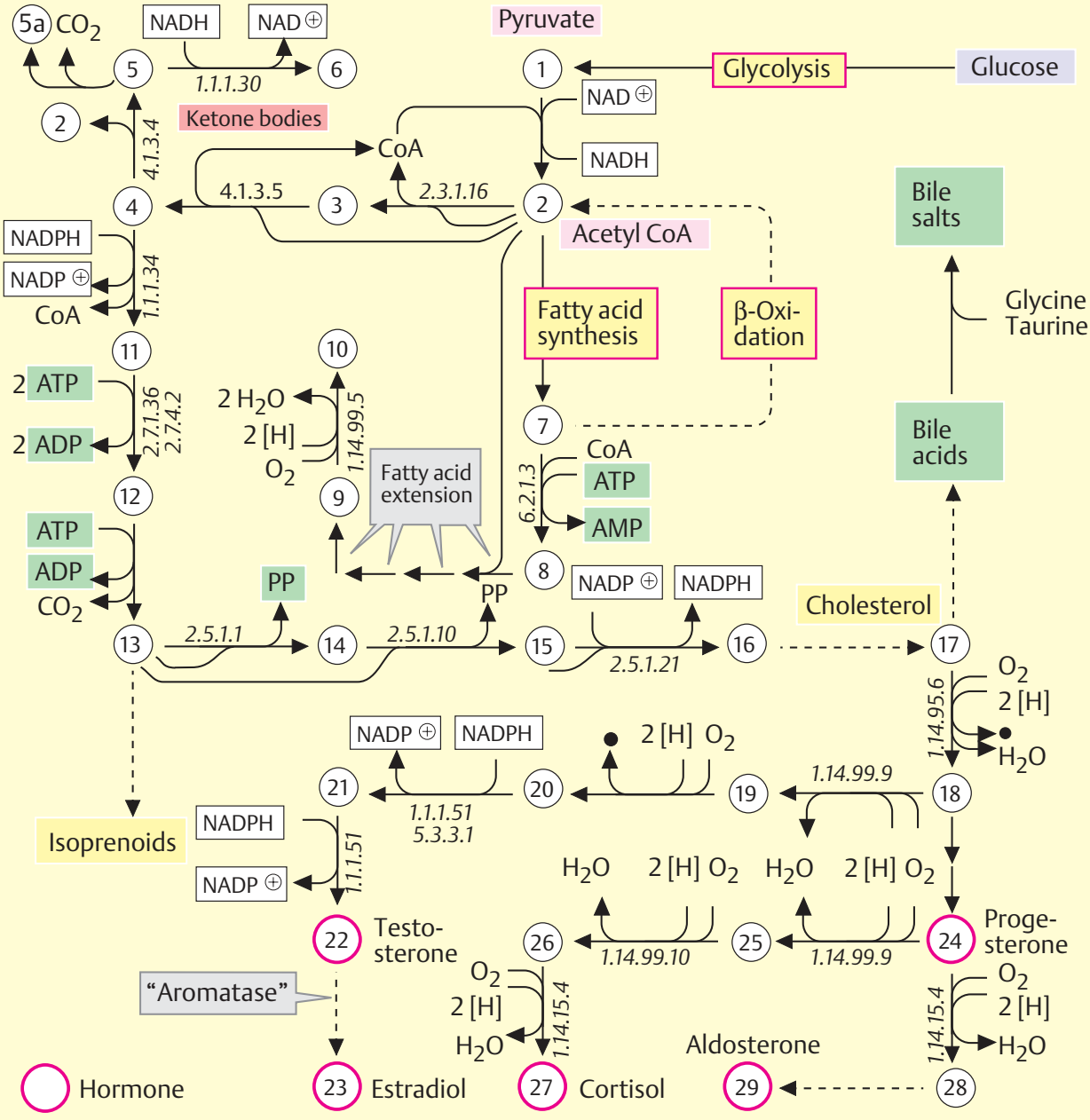
1	Glycogen	9	Ribose 5-phosphate	17	1,3-Bisphosphoglycerate
2	UDP-Glucose	10	Xylulose 5-phosphate	18	3-Phosphoglycerate
3	Glucose 1-phosphate	11	Sedoheptulose 7-phosphate	19	2-Phosphoglycerate
4	Glucose	12	Glyceraldehyde 3-phosphate	20	Phosphoenolpyruvate
5	Glucose 6-phosphate	13	Erythrose 4-phosphate	21	Pyruvate
6	Gluconolactone 6-Ⓟ	14	Fructose 6-phosphate	22	Lactate
7	Gluconate 6-phosphate	15	Fructose 1,6-bisphosphate	23	Oxaloacetate
8	Ribulose 5-phosphate	16	Glycerone-3-phosphate	24	Glycerol
				25	Glycerol 3-phosphate

A. Biosynthesis of fats and membrane lipids



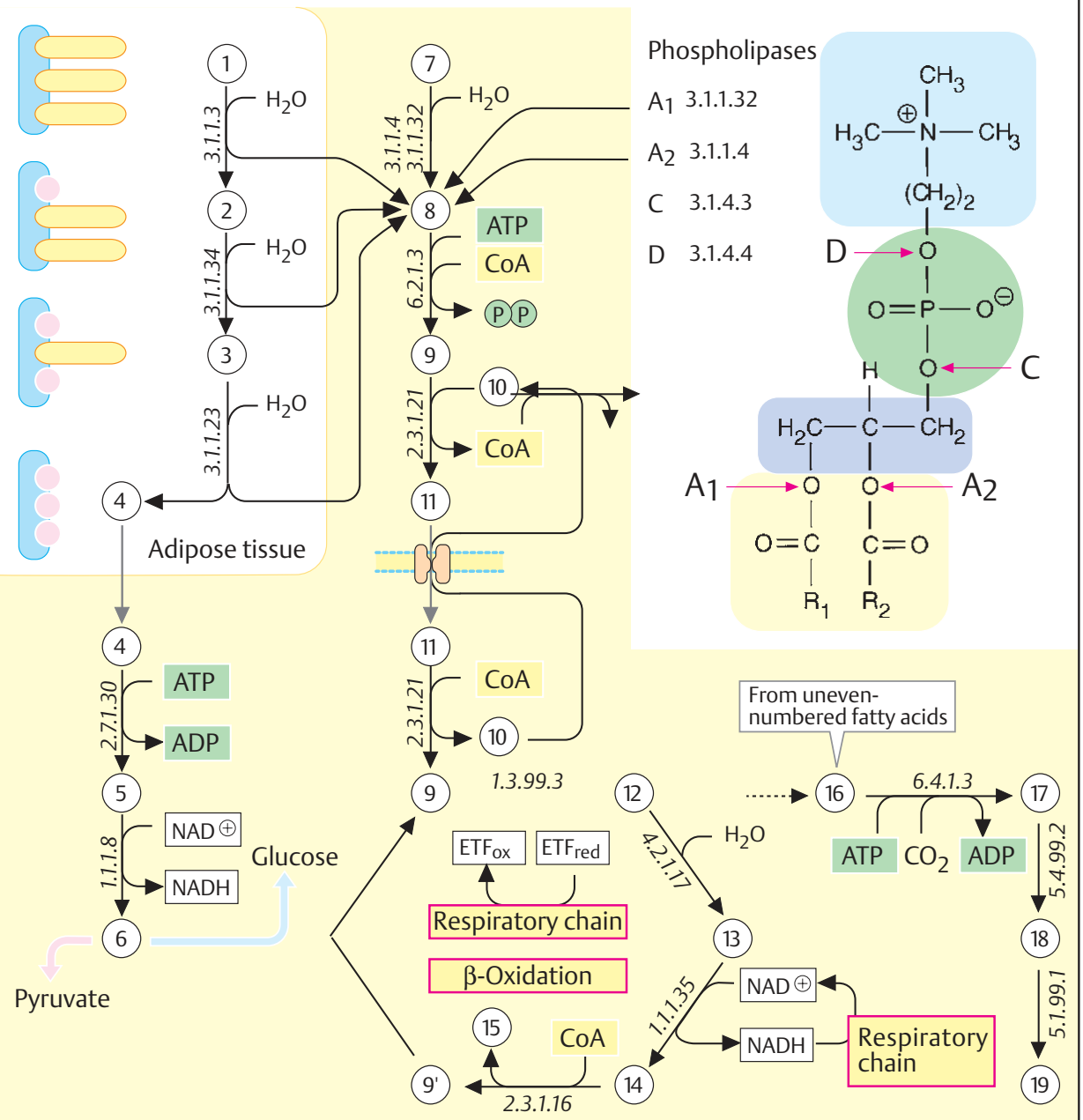
1. Pyruvate
2. Dihydroxyacetone 3-P
3. Acetyl CoA
4. Glycerol
5. Glycerol 3-phosphate
6. Acyl CoA
7. 1-Acylglycerol 3-phosphate
8. 1-Acylglycerone 3-phosphate
9. Phosphatidate
10. CDP-diacylglycerol
11. 1,2-Diacylglycerol
12. Phosphatidylinositol
13. Choline
14. CDP-choline
15. Phosphatidylcholine
16. Ethanolamine
17. CDP-ethanolamine
18. Phosphatidylethanolamine
19. Palmitoyl CoA
20. Phosphatidylserine
21. Sphingosine
22. Serine
23. Ceramide
24. Galactosylceramide
25. Sphingomyelin

A. Synthesis of ketone bodies and steroids



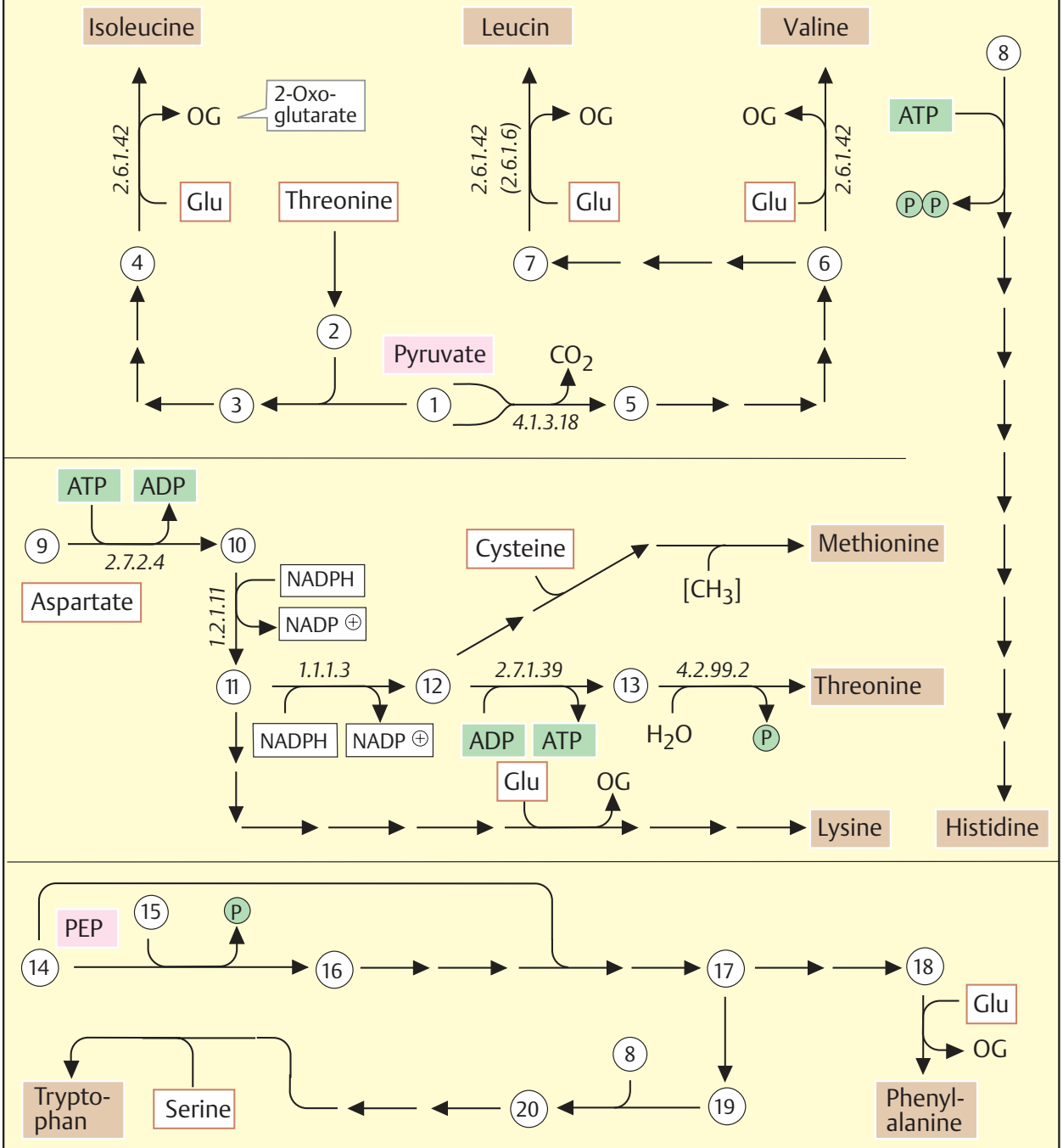
(1) Pyruvate	(10) Oleyl CoA	(20) Dehydroepiandrosterone
(2) Acetyl CoA	(11) Mevalonate	(21) Androstene-3,17-dione
(3) Acetoacetyl CoA	(12) Mevalonate 5-diphosphate	(22) Testosterone
(4) 3-Hydroxy-3-methyl-glutaryl CoA	(13) Isopentenyl diphosphate	(23) Estradiol
(5) Acetoacetate	(14) Geranyl diphosphate	(24) Progesterone
(5a) Acetone	(15) Farnesyl diphosphate	(25) 17-OH-Progesterone
(6) 3-Hydroxybutyrate	(16) Squalene	(26) 11-Deoxycortisol
(7) Palmitate	(17) Cholesterol	(27) Cortisol
(8) Palmitoyl CoA	(18) Pregnenolone	(28) 11-Deoxycorticosterone
(9) Stearoyl CoA	(19) 17-OH-Pregnenolone	(29) Aldosterone

A. Degradation of fats and phospholipids



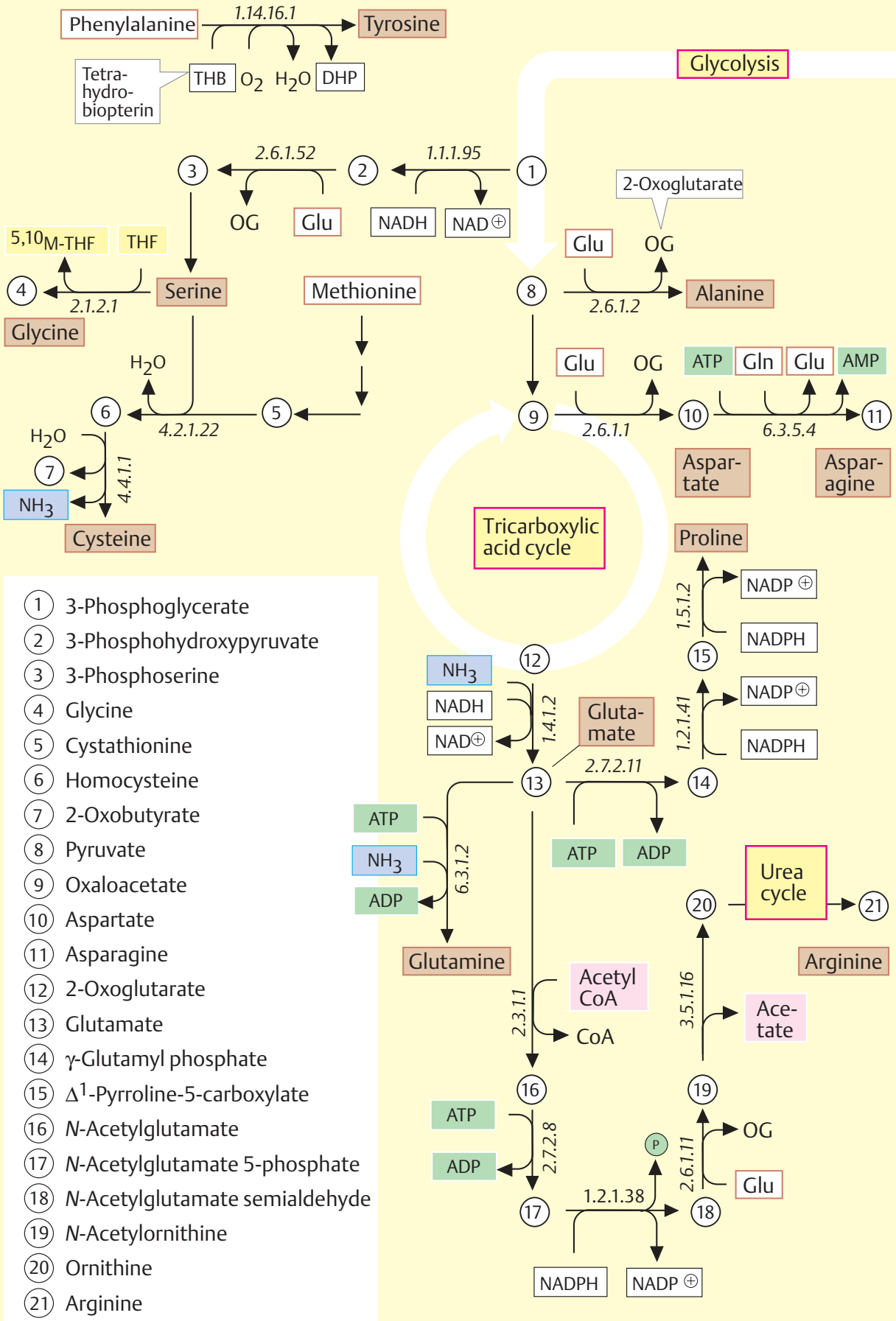
1 Triacylglycerol	8 Free fatty acid	14 3-Oxoacyl CoA
2 Diacylglycerol	9 Acyl CoA	15 Acetyl CoA
3 Monoacylglycerol	9' Shortened acyl CoA	16 Propionyl CoA
4 Glycerol	10 Carnitine	17 (S)-Methylmalonyl CoA
5 Glycerol 3-phosphate	11 Acyl carnitine	18 (R)-Methylmalonyl CoA
6 Glycerone 3-phosphate	12 2,3-Dehydroacyl CoA	19 Succinyl CoA
7 Phospholipid	13 3-Hydroxyacyl CoA	

A. Biosynthesis of the essential amino acids



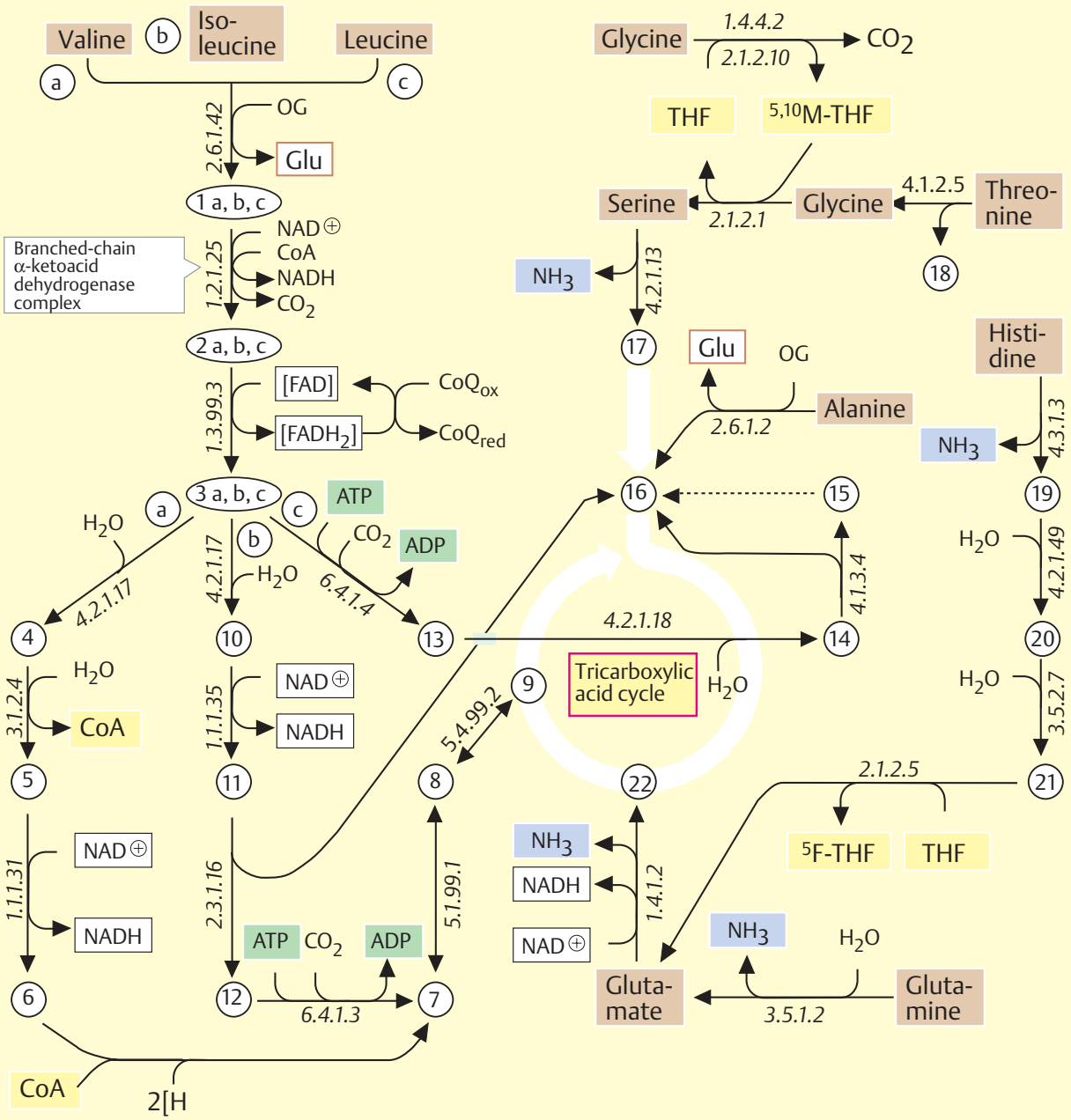
1. Pyruvate
2. 2-Oxobutyrate
3. 2-Aceto-2-hydroxybutyrate
4. 2-Oxo-4-methylvalerate
5. 2-Acetolactate
6. 2-Oxoisovalerate
7. 2-Oxoisocaproate
8. Phosphoribosyl diphosphate
9. Aspartate
10. Aspartyl 4-phosphate
11. Aspartate 4-semialdehyde
12. Homoserine
13. Phosphohomoserine
14. Phosphoenolpyruvate
15. Erythrose 4-phosphate
16. 2-Oxo-3-deoxy-arabinoheptulosonate 7-phosphate
17. Chorismate
18. Phenylpyruvate
19. Anthranilate
20. *N*-(Phosphoribosyl)-anthranilate

A. Biosynthesis of the non-essential amino acids



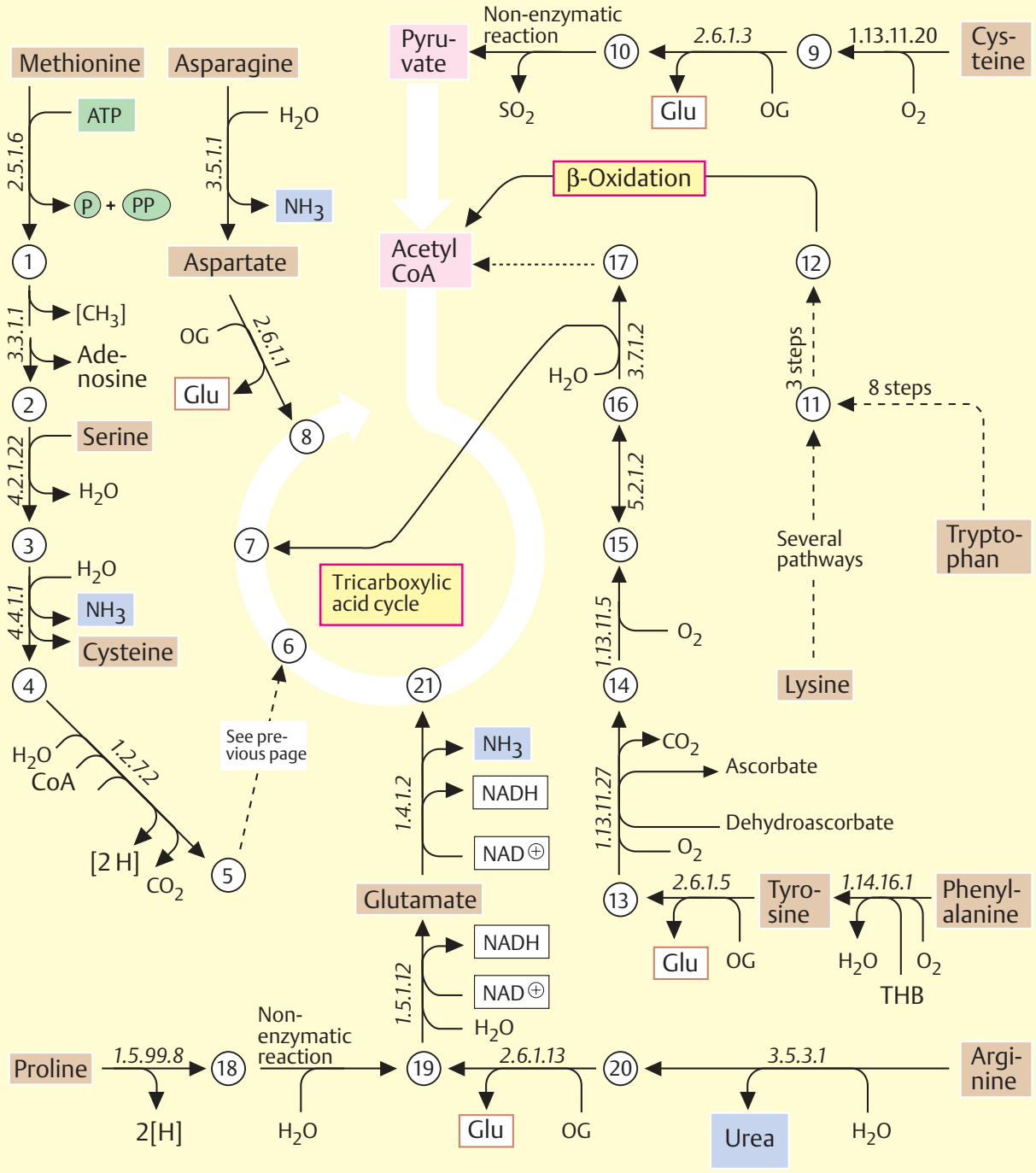
1. 3-Phosphoglycerate
2. 3-Phosphohydroxypyruvate
3. 3-Phosphoserine
4. Glycine
5. Cystathionine
6. Homocysteine
7. 2-Oxobutyrate
8. Pyruvate
9. Oxaloacetate
10. Aspartate
11. Asparagine
12. 2-Oxoglutarate
13. Glutamate
14. γ-Glutamyl phosphate
15. Δ^1-Pyrroline-5-carboxylate
16. *N*-Acetylglutamate
17. *N*-Acetylglutamate 5-phosphate
18. *N*-Acetylglutamate semialdehyde
19. *N*-Acetylornithine
20. Ornithine
21. Arginine

A. Amino acid degradation I



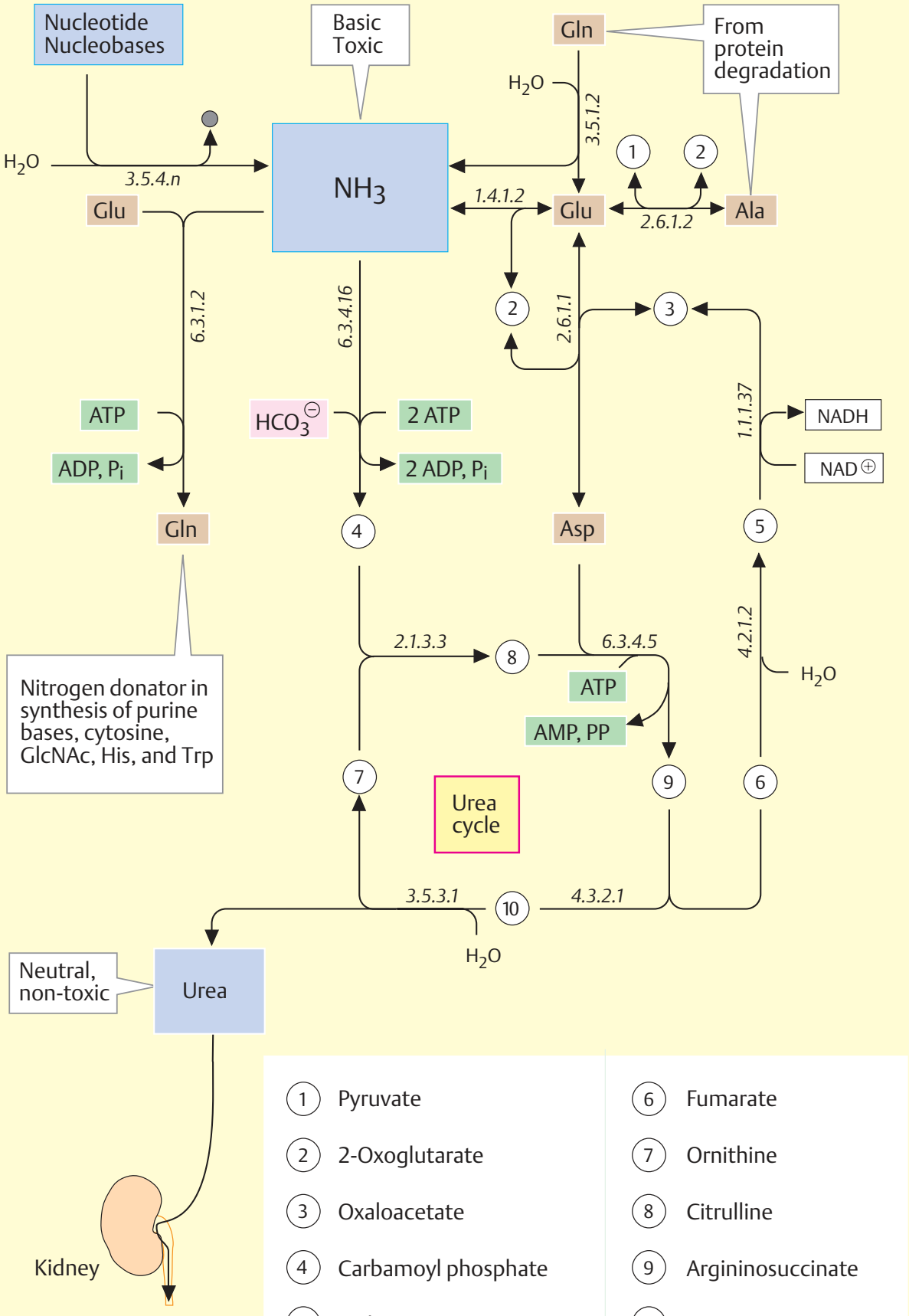
1a	2-Oxoisovalerate	5	3-Hydroxyisobutyrate	15	Acetoacetate
1b	2-Oxo-3-methylvalerate	6	Methylmalonyl-semialdehyde	16	Acetyl CoA
1c	2-Oxoisocapronate	7	(S)-Methylmalonyl CoA	17	Pyruvate
2a	Isobutyryl CoA	8	(R)-Methylmalonyl CoA	18	Acetaldehyde
2b	2-Methylbutyryl CoA	9	Succinyl CoA	19	Urocanate
2c	Isovaleryl CoA	10	2-Methyl-3-hydroxybutyryl CoA	20	Imidazolone-5-propionate
3a	Methylacrylyl CoA	11	2-Methylacetoacetyl CoA	21	*N*-Formimino-glutamate
3b	Tiglyl CoA	12	Propionyl CoA	22	2-Oxoglutarate
3c	3-Methylcrotonyl CoA	13	3-Methylglutaconyl CoA		
4	3-Hydroxyisobutyryl CoA	14	3-Hydroxy-3-methylglutaryl CoA		

A. Amino acid degradation II

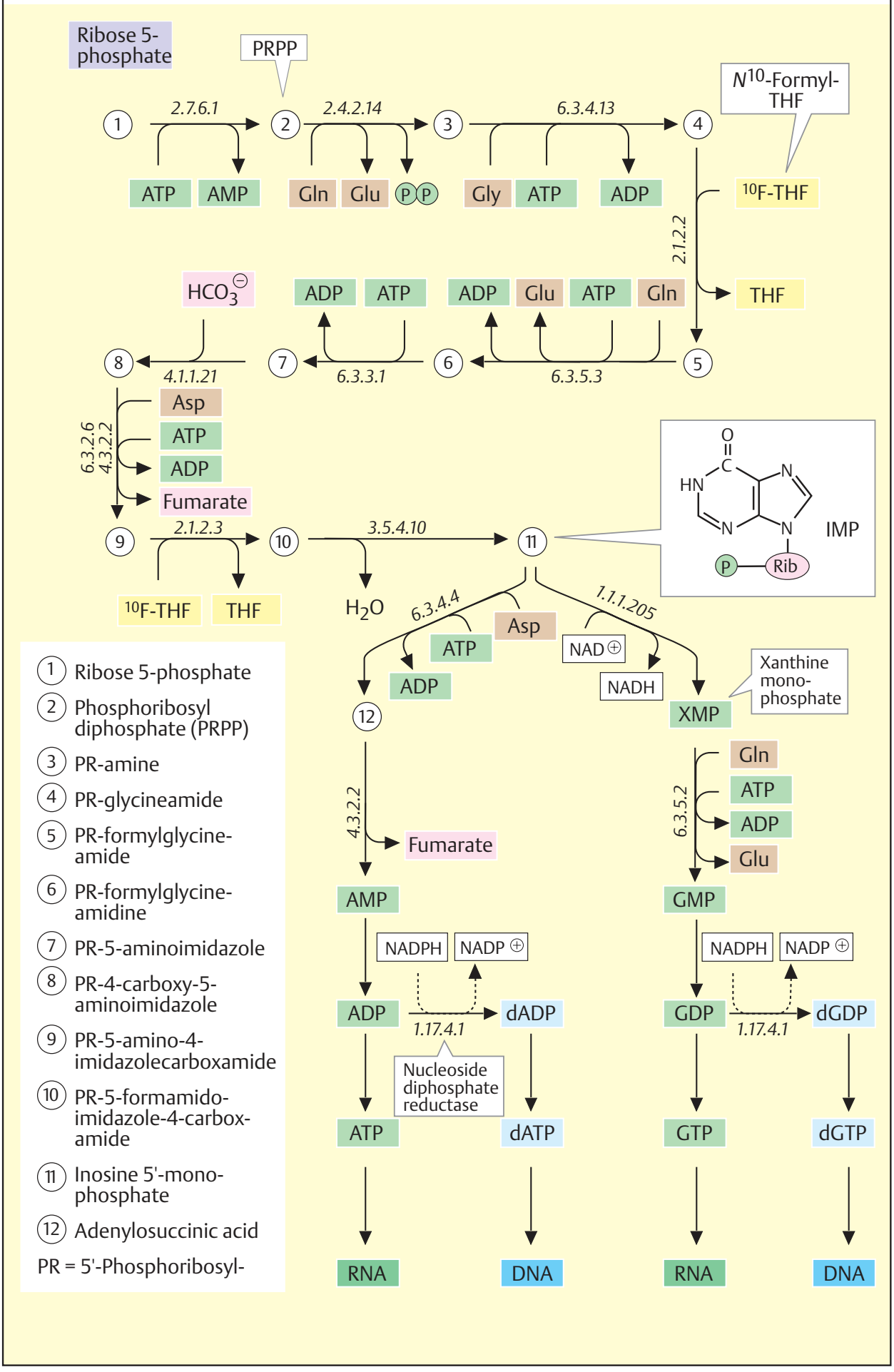


1. *S*-Adenosylmethionine
2. Homocysteine
3. Cystathionine
4. 2-Oxobutyrate
5. Propionyl CoA
6. Succinyl CoA
7. Fumarate
8. Oxaloacetate
9. Cysteine sulfinate
10. 3-Sulfinylpyruvate
11. 2-Oxoadipate
12. Crotonyl CoA
13. 4-Hydroxyphenylpyruvate
14. Homogentisate
15. 4-Maleylacetoacetate
16. Fumarylacetoacetate
17. Acetoacetate
18. Glutamate 4-semialdehyde
19. Δ^1-Pyrroline-5-carboxylate
20. Ornithine
21. 2-Oxoglutarate

A. Ammonia metabolism



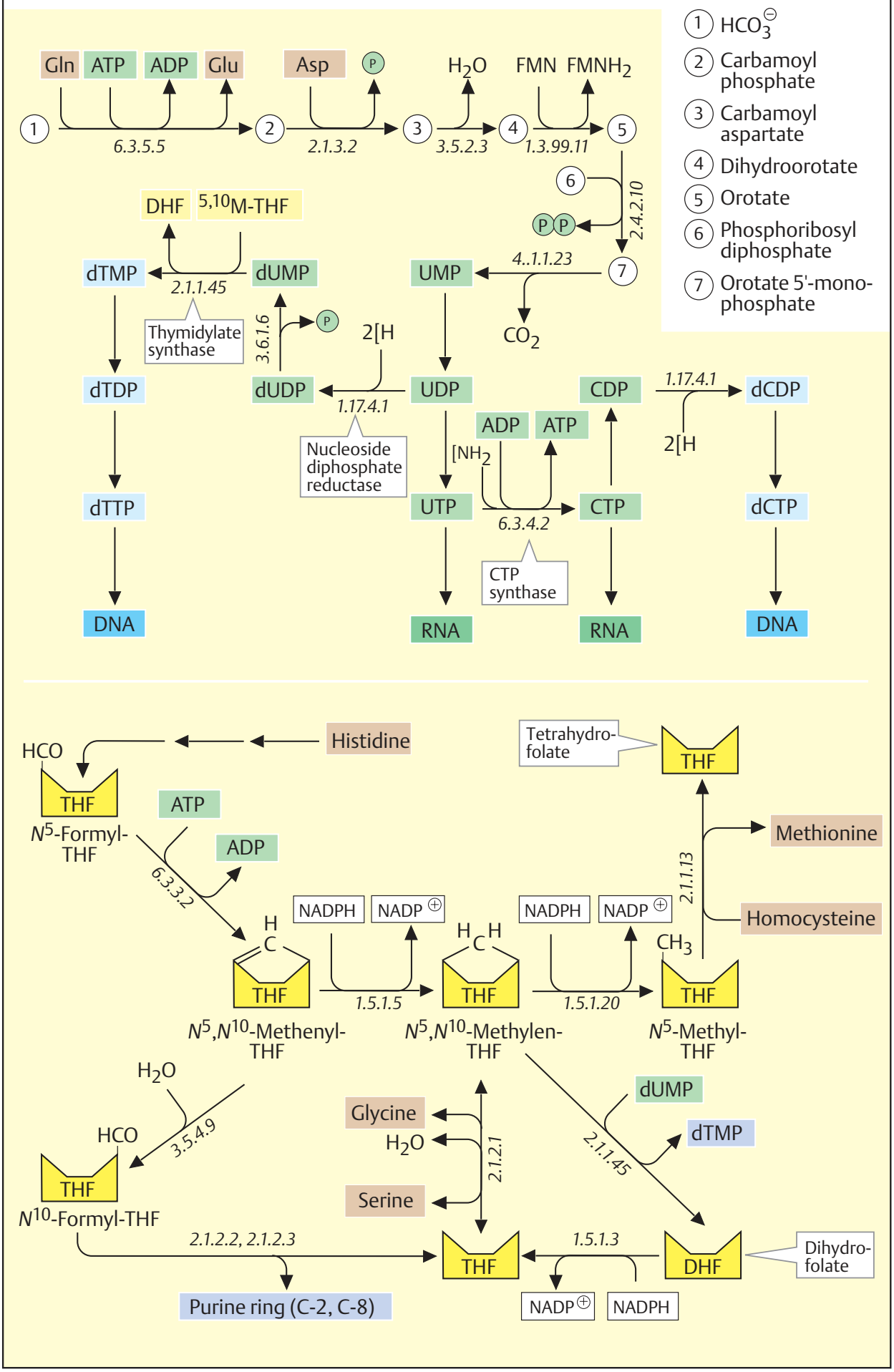
A. Biosynthesis of purine nucleotides



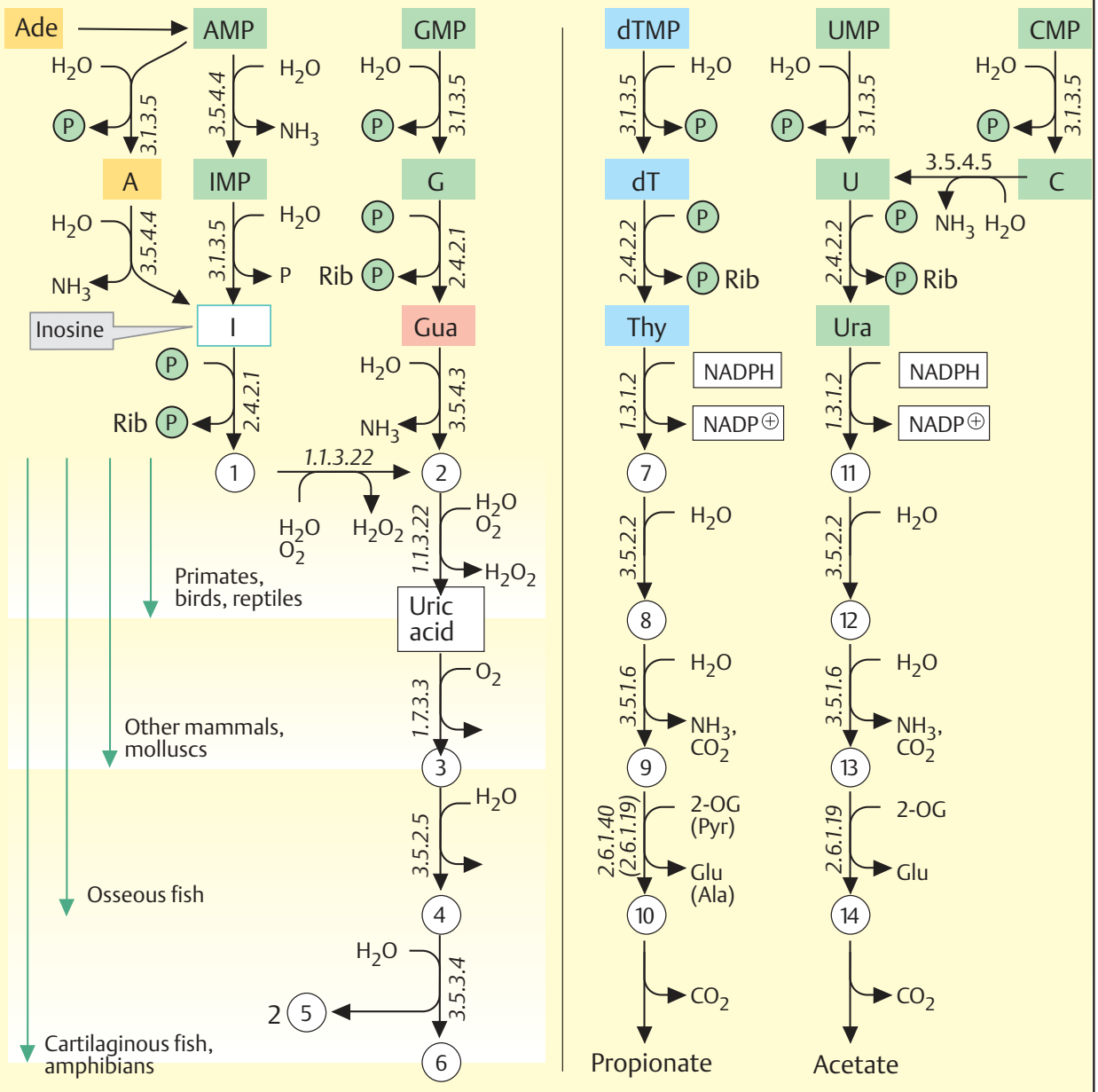
1. Ribose 5-phosphate
2. Phosphoribosyl diphosphate (PRPP)
3. PR-amine
4. PR-glycineamide
5. PR-formylglycine-amide
6. PR-formylglycine-amidine
7. PR-5-aminoimidazole
8. PR-4-carboxy-5-aminoimidazole
9. PR-5-amino-4-imidazolecarboxamide
10. PR-5-formamido-imidazole-4-carbox-amide
11. Inosine 5'-mono-phosphate
12. Adenylosuccinic acid

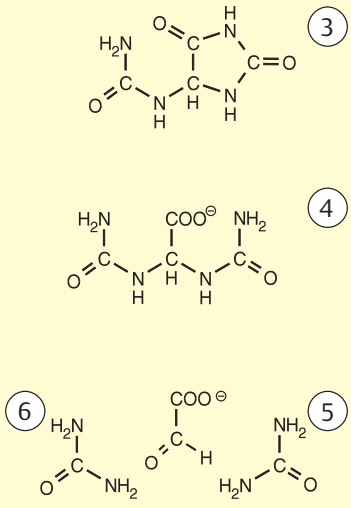
PR = 5'-Phosphoribosyl-

A. Biosynthesis of the pyrimidine nucleotides and C_1 metabolism



A. Nucleotide degradation





1 Hypoxanthine (Hyp)
2 Xanthine (Xan)
3 Allantoin
4 Allantoic acid
5 Glyoxylate
6 Urea
7 Dihydrothymine
8 Carbamoyl-β-amino-isobutyrate
9 β-Aminoisobutyrate
10 2-Methyl-3-oxopropionate
11 Dihydrouracil
12 Carbamoyl-β-alanine
13 β-alanine
14 3-oxopropionate

Annotated enzyme list

Only the enzymes mentioned in this atlas are listed here, from among the more than 2000 enzymes known. The enzyme names are based on the IUBMB's of cial *Enzyme nomenclature 1992*. The additions shown in round brackets belong to the enzyme name, while prosthetic groups and other cofactors are enclosed in square brackets. Common names of enzyme groups are given in italics, and trivial names are shown in quotation marks.

Class 1: Oxidoreductases (catalyze reduction-oxidation reactions)

Subclass 1.n: What is the electron *donor?*
Sub-subclass 1.n.n: What is the electron *acceptor*?

1.1 A –CH–OH group is the donor

1.1.1 $NAD(P)^+$ is the acceptor (*dehydrogenases, reductases*)
1.1.1.1 Alcohol dehydrogenase [Zn^{2+}]
1.1.1.3 Homoserine dehydrogenase
1.1.1.8 Glycerol 3-phosphate dehydrogenase (NAD^+)
1.1.1.21 Aldehyde reductase
1.1.1.27 Lactate dehydrogenase
1.1.1.30 3-Hydroxybutyrate dehydrogenase
1.1.1.31 3-Hydroxyisobutyrate dehydrogenase
1.1.1.34 Hydroxymethylglutaryl-CoA reductase (NADPH)
1.1.1.35 3-Hydroxyacyl-CoA dehydrogenase
1.1.1.37 Malate dehydrogenase
1.1.1.40 Malate dehydrogenase (oxaloacetate-decarboxylating, $NADP^+$)—"malic enzyme"
1.1.1.41 Isocitrate dehydrogenase (NAD^+)
1.1.1.42 Isocitrate dehydrogenase ($NADP^+$)
1.1.1.44 Phosphogluconate dehydrogenase (decarboxylating)
1.1.1.49 Glucose 6-phosphate 1-dehydrogenase
1.1.1.51 3(or 17)β-Hydroxysteroid dehydrogenase
1.1.1.95 Phosphoglycerate dehydrogenase
1.1.1.100 3-Oxoacyl-[ACP] reductase
1.1.1.101 Acylglycerone phosphate reductase
1.1.1.105 Retinol dehydrogenase
1.1.1.145 3β-Hydroxy-Δ^5-steroid dehydrogenase
1.1.1.205 IMP dehydrogenase

1.1.3 Molecular oxygen is the acceptor (*oxidases*)
1.1.3.4 Glucose oxidase [FAD]
1.1.3.8 L-Gulonolactone oxidase
1.1.3.22 Xanthine oxidase [Fe, Mo, FAD]
1.1.99.5 Glycerol-3-phosphate dehydrogenase (FAD)

1.2 An aldehyde or keto group is the donor

1.2.1 $NAD(P)^+$ is the acceptor *(dehydrogenases)*
1.2.1.3 Aldehyde dehydrogenase (NAD^+)
1.2.1.11 Aspartate semialdehyde dehydrogenase
1.2.1.12 Glyceraldehyde 3-phosphate dehydrogenase
1.2.1.13 Glyceraldehyde 3-phosphate dehydrogenase ($NADP^+$) (phosphorylating)
1.2.1.24 Succinate semialdehyde dehydrogenase
1.2.1.25 2-Oxoisovalerate dehydrogenase (acylating)
1.2.1.38 *N*-Acetyl-γ-glutamylphosphate reductase
1.2.1.41 Glutamylphosphate reductase

1.2.4 A disulfide is the acceptor
1.2.4.1 Pyruvate dehydrogenase (lipoamide) [TPP]
1.2.4.2 Oxoglutarate dehydrogenase (lipoamide) [TPP]

1.2.7 An Fe/S protein is the acceptor
1.2.7.2 2-Oxobutyrate synthase

1.3 A –CH–CH– group is the donor
1.3.1.10 Enoyl-[ACP] reductase (NADPH)
1.3.1.24 Biliverdin reductase
1.3.1.34 2,4-Dienoyl-CoA reductase
1.3.5.1 Succinate dehydrogenase (ubiquinone) [FAD, Fe_2S_2, Fe_4S_4], "complex II"
1.3.99.3 Acyl-CoA dehydrogenase [FAD]
1.3.99.11 Dihydroorotate dehydrogenase [FMN]

1.4 A –CH–NH2 group is the donor
1.4.1.2 Glutamate dehydrogenase
1.4.3.4 Amine oxidase [FAD], "monoamine oxidase (MAO)"
1.4.3.13 Protein lysine 6-oxidase [Cu]
1.4.4.2 Glycine dehydrogenase (decarboxylating) [PLP]

1.5 A –CH–NH group is the donor
1.5.1.2 Pyrroline-5-carboxylate reductase
1.5.1.3 Dihydrofolate reductase
1.5.1.5 Methylenetetrahydrofolate dehydrogenase ($NADP^+$)
1.5.1.12 1-Pyrroline-5-carboxylate dehydrogenase
1.5.1.20 Methylenetetrahydrofolate reductase (NADPH) [FAD]
1.5.5.1 Electron-transferring flavoprotein (ETF) dehydrogenase [Fe_4S_4]
1.5.99.8 Proline dehydrogenase [FAD]

1.6 NAD(P)H is the donor
16.4.2 Glutathione reductase (NADPH) [FAD]
1.6.4.5 Thioredoxin reductase (NADPH) [FAD]
1.6.5.3 NADH dehydrogenase (ubiquinone) [FAD, Fe_2S_2, Fe_4S_4]—"complex I"

1.8 A sulfur group is the donor
1.8.1.4 Dihydrolipoamide dehydrogenase [FAD]

1.9 A heme group is the donor
1.9.3.1 Cytochrome *c* oxidase [heme, Cu, Zn] – "cytochrome oxidase," "complex IV"

1.10 A diphenol is the donor
1.10.2.2 Ubiquinol cytochrome *c* reductase [heme, Fe_2S_2]—"complex III"

1.11 A peroxide is the acceptor (*peroxidases*)
1.11.1.6 Catalase [heme]
1.11.1.7 Peroxidase [heme]
1.11.1.9 Glutathione peroxidase [Se]
1.11.1.12 Lipid hydroperoxide glutathione peroxidase [Se]

1.13 Molecular oxygen is incorporated into the electron donor (*oxygenases*)

1.13.11 One donor, both O atoms are incorporated (*dioxygenases*)
1.13.11.5 Homogentisate 1,2-dioxygenase [Fe]
1.13.11.20 Cysteine dioxygenase [Fe]
1.13.11.27 4-Hydroxyphenylpyruvate dioxygenase [ascorbate]
1.13.11.n Arachidonate lipoxygenases

1.14 Two donors, one O atom is incorporated into both (*monooxygenases, hydroxylases*)
1.14.11.2 Procollagen proline 4-dioxygenase [Fe, ascorbate]—"proline hydroxylase"
1.14.11.4 Procollagen lysine 5-dioxygenase [Fe, ascorbate]—"lysine hydroxylase"
1.14.13.13 Calcidiol 1-monooxygenase [heme]
1.14.15.4 Steroid 11β-monooxygenase [heme]
1.14.15.6 Cholesterol monooxygenase (side-chain-cleaving) [heme]
1.14.16.1 Phenylalanine 4-monooxygenase [Fe, tetrahydrobiopterin]
1.14.16.2 Tyrosine 3-monooxygenase [Fe, tetrahydrobiopterin]
1.14.17.1 Dopamine β-monooxygenase [Cu]
1.14.99.1 Prostaglandin H-synthase [heme]
1.14.99.3 Heme oxygenase (decyclizing) [heme]
1.14.99.5 Stearoyl-CoA desaturase [heme]
1.14.99.9 Steroid 17α-monooxygenase [heme]
1.14.99.10 Steroid 21-monooxygenase [heme]

1.15 A superoxide radical is the acceptor
1.15.1.1 Superoxide dismutase

1.17 A $-CH_2$ group is the donor
1.17.4.1 Ribonucleoside diphosphate reductase [Fe]—"ribonucleotide reductase"

1.18 Reduced ferredoxin is the donor
1.18.1.2 Ferredoxin-$NADP^+$ reductase [FAD]
1.18.6.1 Nitrogenase [Fe, Mo, Fe_4S_4]

Class 2: Transferases (catalyze the transfer of groups from one molecule to another)

Subclass 2.n: *Which group* is transferred?

2.1 A C_1 group is transferred

2.1.1 A methyl group
2.1.1.2 Guanidinoacetate *N*-methyltransferase
2.1.1.6 Catechol *O*-methyltransferase
2.1.1.13 5-Methyltetrahydrofolate-homocysteine *S*-methyltransferase
2.1.1.28 Phenylethanolamine *N*-methyltransferase
2.1.1.45 Thymidylate synthase
2.1.1.67 Thiopurine methyltransferase

2.1.2 A formyl group
2.1.2.1 Glycine hydroxymethyltransferase [PLP]
2.1.2.2 Phosphoribosylglycinamide formyltransferase
2.1.2.3 Phosphoribosylaminoimidazolecarboxamide formyltransferase
2.1.2.5 Glutamate formiminotransferase [PLP]
2.1.2.10 Aminomethyltransferase

2.1.3 A carbamoyl group
2.1.3.2 Aspartate carbamoyltransferase [Zn^{2+}]

2.1.3.3 Ornithine carbamoyltransferase

2.1.4 An amidino group
2.1.4.1 Glycine amidinotransferase

2.2 An aldehyde or ketone residue is transferred
2.2.1.1 Transketolase [TPP]
2.2.1.2 Transaldolase

2.3 An acyl group is transferred

2.3.1 With acyl-CoA as donor
2.3.1.1 Amino acid *N*-acetyltransferase
2.3.1.6 Choline *O*-acetyltransferase
2.3.1.12 Dihydrolipoamide acetyltransferase [lipoamide]
2.3.1.15 Glycerol 3-phosphate *O*-acyltransferase
2.3.1.16 Acetyl-CoA acyltransferase
2.3.1.20 Diacylglycerol *O*-acyltransferase
2.3.1.21 Carnitine *O*-palmitoyltransferase
2.3.1.22 Acylglycerol *O*-palmitoyltransferase
2.3.1.24 Sphingosine *N*-acyltransferase
2.3.1.37 5-Aminolevulinate synthase [PLP]
2.3.1.38 [ACP] *S*-acetyltransferase
2.3.1.39 [ACP] *S*-malonyltransferase
2.3.1.41 3-Oxoacyl-[ACP] synthase
2.3.1.42 Glycerone phosphate *O*-acyltransferase
2.3.1.43 Phosphatidylcholine-sterol acyltransferase—"lecithin-cholesterol acyltransferase (LCAT)"
2.3.1.51 Acylgylcerol-3-phosphate *O*-acyltransferase
2.3.1.61 Dihydrolipoamide succinyltransferase
2.3.1.85 Fatty-acid synthase

2.3.2 An aminoacyl group is transferred
2.3.2.2 γ-glutamyltransferase
2.3.2.12 Peptidyltransferase (*a ribozyme*)
2.3.2.13 Protein-glutamine γ-glutamyltransferase [Ca]—"fibrin-stabilizing factor"

2.4 A glycosyl group is transferred

2.4.1 A hexose residue
2.4.1.1 Phosphorylase [PLP]—"glycogen (starch) phosphorylase"
2.4.1.11 Glycogen (starch) synthase
2.4.1.17 Glucuronosyltransferase
2.4.1.18 1,4-α-Glucan branching enzyme
2.4.1.25 4-α-Glucanotransferase
2.4.1.47 *N*-Acylsphingosine galactosyltransferase
2.4.1.119 Protein glycotransferase

2.4.2 A pentose residue
2.4.2.7 Adenine phosphoribosyltransferase
2.4.2.8 Hypoxanthine phosphoribosyltransferase
2.4.2.10 Orotate phosphoribosyltransferase
2.4.2.14 Amidophosphoribosyl transferase

2.5 An alkyl or aryl group is transferred
2.5.1.1 Dimethylallyltransferase
2.5.1.6 Methionine adenosyltransferase
2.5.1.10 Geranyltransferase
2.5.1.21 Farnesyl diphosphate farnesyltransferase

2.6 A nitrogen-containing group is transferred

2.6.1 An amino group (*transaminases*)
2.6.1.1 Aspartate transaminase [PLP]—"GOT"
2.6.1.2 Alanine transaminase [PLP]—"GPT"

2.6.1.3 Cysteine transaminase [PLP]
2.6.1.5 Tyrosine transaminase [PLP]
2.6.1.6 Leucine transaminase (PLP]
2.6.1.11 Acetylornithine transaminase [PLP]
2.6.1.13 Ornithine transaminase [PLP]
2.6.1.19 4-Aminobutyrate transaminase [PLP]
2.6.1.42 Branched-chain amino acid transaminase [PLP]
2.6.1.52 Phosphoserine transaminase [PLP]

2.7 A phosphorus-containing group is transferred (*kinases*)

2.7.1 With –CH–OH as acceptor
2.7.1.1 Hexokinase
2.7.1.3 Ketohexokinase
2.7.1.6 Galactokinase
2.7.1.11 6-Phosphofructokinase
2.7.1.19 Phosphoribulokinase
2.7.1.28 Triokinase (triosekinase)
2.7.1.30 Glycerol kinase
2.7.1.32 Choline kinase
2.7.1.36 Mevalonate kinase
2.7.1.37 Protein kinase
2.7.1.38 Phosphorylase kinase
2.7.1.39 Homoserine kinase
2.7.1.40 Pyruvate kinase
2.7.1.67 1-Phosphatidylinositol-4-kinase
2.7.1.68 1-Phosphatidylinositol 4-phosphate kinase
2.7.1.82 Ethanolamine kinase
2.7.1.99 [Pyruvate dehydrogenase] kinase
2.7.1.105 6-Phosphofructo-2-kinase
2.7.1.112 Protein tyrosine kinase

2.7.2 With –CO–OH as acceptor
2.7.2.3 Phosphoglycerate kinase
2.7.2.4 Aspartate kinase
2.7.2.8 Acetylglutamate kinase
2.7.2.11 Glutamate 5-kinase

2.7.3 With a nitrogen-containing group as acceptor
2.7.3.2 Creatine kinase

2.7.4 With a phosphate group as acceptor
2.7.4.2 Phosphomevalonate kinase
2.7.4.3 Adenylate kinase
2.7.4.4 Nucleoside phosphate kinase
2.7.4.6 Nucleoside diphosphate kinase

2.7.6 A diphosphate residue is transferred
2.7.6.1 Ribose phosphate pyrophosphokinase

2.7.7 A nucleotide is transferred
2.7.7.6 DNA-directed RNA polymerase—"RNA polymerase"
2.7.7.7 DNA-directed DNA polymerase—"DNA polymerase"
2.7.7.9 UTP-glucose-l-phosphate uridyltransferase
2.7.7.12 Hexose-1-phosphate uridyltransferase
2.7.7.14 Ethanolamine phosphate cytidyltransferase

2.7.7.15 Choline phosphate cytidyltransferase
2.7.7.41 Phosphatidate cytidyltransferase
2.7.7.49 RNA-directed DNA polymerase—"reverse transcriptase"

2.7.8 Another substituted phosphate is transferred
2.7.8.1 Ethanolaminephosphotransferase
2.7.8.2 Diacylglycerol cholinephosphotransferase
2.7.8.11 CDPdiacylglycerol-inositol 3-phosphatidyltransferase
2.7.8.16 1-Alkyl-2-acetylglycerol cholinephosphotransferase
2.7.8.17 *N*-Acetylglucosaminephosphotransferase

Class 3: Hydrolases (catalyze bond cleavage by hydrolysis)

Subclass 3.n: *What kind of bond* is hydrolyzed?

3.1 An ester bond is hydrolyzed (*esterases*)

3.1.1 In carboxylic acid esters
3.1.1.2 Arylesterase
3.1.1.3 Triacylglycerol lipase
3.1.1.4 Phospholipase A_2
3.1.1.7 Acetylcholinesterase
3.1.1.13 Cholesterol esterase
3.1.1.17 Gluconolactonase
3.1.1.32 Phospholipase A_1
3.1.1.34 Lipoprotein lipase, diacylglycerol lipase

3.1.2 In thioesters 3.1.2.4
3-Hydroxyisobutyryl-CoA hydrolase
3.1.2.14 Acyl-[ACP] hydrolase

3.1.3 In phosphoric acid monoesters (*phosphatases*)
3.1.3.1 Alkaline phosphatase [Zn^{2+}]
3.1.3.2 Acid phosphatase
3.1.3.4 Phosphatidate phosphatase
3.1.3.9 Glucose 6-phosphatase
3.1.3.11 Fructose bisphosphatase
3.1.3.13 Bisphosphoglycerate phosphatase
3.1.3.16 Phosphoprotein phosphatase
3.1.3.37 Sedoheptulose bisphosphatase
3.1.3.43 [Pyruvate dehydrogenase] phosphatase
3.1.3.46 Fructose-2,6-bisphosphate 2-phosphatase
3.1.3.n Polynucleotidases

3.1.4 In phosphoric acid diesters (*phosphodiesterases*)
3.1.4.1 Phosphodiesterase
3.1.4.3 Phospholipase C
3.1.4.4 Phospholipase D
3.1.4.17 3′,5′-cNMP phosphodiesterase
3.1.4.35 3′,5′-cGMP phosphodiesterase
3.1.4.45 *N*-Acetylglucosaminyl phosphodiesterase

3.1.21 In DNA
3.1.21.1 Deoxyribonuclease I
3.1.21.4 Site-specific deoxyribonuclease (type II)—"restriction endonuclease"

3.10.26–7 **In RNA**
3.1.26.4 Ribonuclease H
3.1.27.5 Pancreatic ribonuclease

3.2 **A glycosidic bond is hydrolyzed** (*glycosidases*)

3.2.1 **In *O*-glycosides**
3.2.1.1 α-Amylase
3.2.1.10 Oligo-1,6-glucosidase
3.2.1.17 Lysozyme
3.2.1.18 Neuraminidase
3.2.1.20 α-Glucosidase
3.2.1.23 β-Galactosidase
3.2.1.24 α -Mannosidase
3.2.1.26 β-Fructofuranosidase—"saccharase," "invertase"
3.2.1.28 α,α-Trehalase
3.2.1.33 Amylo-1,6-glucosidase
3.2.1.48 Sucrose α-glucosidase
3.2.1.52 β-*N*-Acetylhexosaminidase
3.2.2.n Nucleosidases

3.3 **An ether bond is hydrolyzed**
3.3.1.1 Adenosylhomocysteinase

3.4 **A peptide bond is hydrolyzed** (*peptidases*)

3.4.11 **Aminopeptidases** (*N*-terminal exopeptidases)
3.4.11.n Various aminopeptidases [Zn^{2+}]

3.4.13 **Dipeptidases** (act on dipeptides only)
3.4.13.n Various dipeptidases [Zn^{2+}]

3.4.15 **Peptidyl dipeptidases** (*C*-terminal exopeptidases, releasing dipeptides)
3.4.15.1 Peptidyl-dipeptidase A [Zn^{2+}]—"angiotensin-converting enzyme (ACE)"

3.4.17 **Carboxypeptidases** (*C*-terminal exopeptidases)
3.4.17.1 Carboxypeptidase A [Zn^{2+}]
3.4.17.2 Carboxypeptidase B [Zn^{2+}]
3.4.17.8 Muramoylpentapeptide carboxypeptidase

3.4.21 **Serine proteinases** (endopeptidases)
3.4.21.1 Chymotrypsin
3.4.21.4 Trypsin
3.4.21.5 Thrombin
3.4.21.6 Coagulation factor Xa—"Stuart–Prower factor"
3.4.21.7 Plasmin
3.4.21.9 Enteropeptidase—"enterokinase"
3.4.21.21 Coagulation factor VIIa—"proconvertin"
3.4.21.22 Coagulation factor IXa—"Christmas factor"
3.4.21.27 Coagulation factor XIa—"plasma thromboplastin antecedent"
3.4.21.34 Plasma kallikrein
3.4.21.35 Tissue kallikrein
3.4.21.36 Elastase
3.4.21.38 Coagulation factor XIIa—"Hageman factor"
3.4.21.43 C3/C5 convertase (complement—classical pathway)
3.4.21.47 C3/C5 convertase (complement—alternative pathway)

3.4.21.68 Plasminogen activator (tissue)—"tissue plasminogen activator (t-PA)"
3.4.21.73 Plasminogen activator (urine)—"urokinase"

3.4.22 Cysteine proteinases (*endopeptidases*)
3.4.22.2 Papain

3.4.23 Aspartate proteinases (*endopeptidases*)
3.4.23.1 Pepsin A
3.4.23.2 Pepsin B
3.4.23.3 Gastricsin (pepsin C)
3.4.23.4 Chymosin
3.4.23.15 Renin

3.4.24 Metalloproteinases (*endopeptidases*)
3.4.24.7 Collagenase

3.4.99 Other peptidases
3.4.99.36 Signal peptidase

3.5 Another amide bond is hydrolyzed (*amidases*)
3.5.1.1 Asparaginase
3.5.1.2 Glutaminase
3.5.1.16 Acetylornithine deacetylase [Zn^{2+}]
3.5.2.3 Dihydroorotase
3.5.2.7 Imidazolonepropionase
3.5.3.1 Arginase
3.5.4.6 AMP deaminase
3.5.4.9 Methylenetetrahydrofolate cyclohydrolase
3.5.4.10 IMP cyclohydrolase

3.6 An anhydride bond is hydrolyzed
3.6.1.6 Nucleoside diphosphatase
3.6.1.32 Myosin ATPase
3.6.1.34 H^+-transporting ATP synthase—"ATP synthase," "complex V"
3.6.1.35 H^+-transporting ATPase
3.6.1.36 H^+/K^+-exchanging ATPase
3.6.1.37 Na^+/K^+-exchanging ATPase—"Na^+/K^+-ATPase"
3.6.1.38 Ca^{2+}-transporting ATPase

3.7 A C–C bond is hydrolyzed
3.7.1.2 Fumarylacetoacetase

Class 4: Lyases (cleave or form bonds without oxidative or hydrolytic steps)

Subclass 4.n: *What kind of bond* is formed or cleaved?

4.1 A C–C bond is formed or cleaved

4.1.1 Carboxy-lyases (*carboxylases, decarboxylases*)
4.1.1.1 Pyruvate decarboxylase [TPP]
4.1.1.15 Glutamate decarboxylase [PLP]
4.1.1.21 Phosphoribosylaminoimidazole carboxylase
4.1.1.23 Orotidine-5′-phosphate decarboxylase
4.1.1.28 Aromatic L-amino acid decarboxylase [PLP]
4.1.1.32 Phosphoenolpyruvate carboxykinase (GTP)
4.1.1.39 Ribulose bisphosphate carboxylase [Cu]—"rubisco"

4.1.2 Acting on aldehydes or ketones
4.1.2.5 Threonine aldolase [PLP]
4.1.2.13 Fructose bisphosphate aldolase—"aldolase"
4.1.3.4 Hydroxymethylglutaryl-CoA lyase
4.1.3.5 Hydroxymethylglutaryl-CoA synthase
4.1.3.7 Citrate synthase
4.1.3.8 ATP-citrate lyase
4.1.3.18 Acetolactate synthase [TPP, flavin]

4.1.99 Other C–C lyases
4.1.99.3 Deoxyribodipyrimidine photolyase [FAD]—"photolyase"

4.2 A C–O bond is formed or cleaved

4.2.1 Hydrolyases (*hydratases, dehydratases*)
4.2.1.1 Carbonate dehydratase [Zn^{2+}]—"carbonic anhydrase"
4.2.1.2 Fumarate hydratase—"fumarase"
4.2.1.3 Aconitate hydratase [Fe_4S_4]—"aconitase"
4.2.1.11 Phosphopyruvate hydratase—"enolase"
4.2.1.13 Serine dehydratase
4.2.1.17 Enoyl-CoA hydratase
4.2.1.18 Methylglutaconyl-CoA hydratase
4.2.1.22 Cystathionine β-synthase [PLP]
4.2.1.24 Porphobilinogen synthase
4.2.1.49 Urocanate hydratase
4.2.1.61 3-Hydroxypalmitoyl-[ACP] dehydratase
4.2.1.75 Uroporphyrinogen III synthase

4.2.99 Other C–O lyases
4.2.99.2 Threonine synthase [PLP]

4.3 A C–N bond is formed or cleaved

4.3.1 Ammonia lyases 4.3.1.3
Histidine ammonia lyase
4.3.1.8 Hydroxymethylbilane synthase

4.3.2 Amidine lyases 4.3.2.1
Argininosuccinate lyase
4.3.2.2 Adenylosuccinate lyase

4.4 A C–S bond is formed or cleaved
4.4.1.1 Cystathionine γ-lyase [PLP]

4.6 A P–O bond is formed or cleaved
4.6.1.1 Adenylate cyclase
4.6.1.2 Guanylate cyclase

Class 5: Isomerases (catalyze changes within one molecule)

Subclass 5.n: *What kind of isomerization* is taking place?

5.1 A racemization or epimerization (*epimerases*)
5.1.3.1 Ribulose phosphate 3-epimerase
5.1.3.2 UDPglucose 4-epimerase
5.1.3.4 L-Ribulose phosphate 4-epimerase
5.1.99.1 Methylmalonyl-CoA epimerase

5.2 **A *cis–trans* isomerization**
5.2.1.2 Maleylacetoacetate isomerase
5.2.1.3 Retinal isomerase
5.2.1.8 Peptidyl proline *cis–trans*-isomerase

5.3 **An intramolecular electron transfer**
5.3.1.1 Triose phosphate isomerase
5.3.1.6 Ribose 5-phosphate isomerase
5.3.1.9 Glucose 6-phosphate isomerase
5.3.3.1 Steroid Δ-isomerase
5.3.3.8 Enoyl-CoA isomerase
5.3.4.1 Protein disulfide isomerase

5.4 **An intramolecular group transfer** (*mutases*)
5.4.2.1 Phosphoglycerate mutase
5.4.2.2 Phosphoglucomutase
5.4.2.4 Bisphosphoglycerate mutase
5.4.99.2 Methylmalonyl-CoA mutase [cobamide]

5.99 **Another kind of isomerization**
5.99.1.2 DNA topoisomerase (type I)—"DNA helicase"
5.99.1.3 DNA topoisomerase (ATP-hydrolyzing, type II)—"DNA gyrase"

Class 6: Ligases (join two molecules with hydrolysis of an "energy-rich" bond)

Subclass 6.n: *What kind of bond* is formed?

6.1 **A C–O bond is formed**
6.1.1.n (Amino acid)-tRNA ligases (*aminoacyl-tRNA synthetases*)

6.2 **A C–S bond is formed**
6.2.1.1 Acetate-CoA ligase
6.2.1.3 Long-chain fatty-acid-CoA ligase
6.2.1.4 Succinate-CoA ligase (GDP-forming)—"thiokinase"

6.3 **A C–N bond is formed**
6.3.1.2 Glutamate-NH_3 ligase—"glutamine synthetase"
6.3.2.6 Phosphoribosylaminoimidazolesuccinocarboxamide synthase *(sorry!)*
6.3.3.1 Phosphoribosylformylglycinamidine cycloligase
6.3.3.2 5-Formyltetrahydrofolate cycloligase
6.3.4.2 CTP synthase
6.3.4.4 Adenylosuccinate synthase
6.3.4.5 Argininosuccinate synthase
6.3.4.13 Phosphoribosylamine glycine ligase
6.3.4.16 Carbamoylphosphate synthase (NH_3)
6.3.5.2 GMP synthase (glutamine-hydrolyzing)
6.3.5.3 Phosphoribosylformylglycinamidine synthase
6.3.5.4 Asparagine synthase (glutamine-hydrolyzing)
6.3.5.5 Carbamoylphosphate synthase (glutamine-hydrolyzing)

6.4 **A C–C bond is formed**
6.4.1.1 Pyruvate carboxylase [biotin]
6.4.1.2 Acetyl-CoA carboxylase [biotin]
6.4.1.3 Propionyl-CoA carboxylase [biotin]
6.4.1.4 Methylcrotonyl-CoA carboxylase [biotin]

6.5 **A P–O bond is formed**
6.5.1.1 DNA ligase (ATP)

Abbreviations

Abbreviations for amino acids, p. 60
For bases and nucleosides, p. 80
For monosaccharides, p. 38

AA	Amino acid
ACE	Angiotensin-converting enzyme (peptidyl-dipeptidase A)
ACP	Acyl carrier protein
ACTH	Adrenocorticotropic hormone (corticotropin)
ADH	Antidiuretic hormone (adiuretin, vasopressin)
ADP	Adenosine 5′-diphosphate
AIDS	Acquired immunodeficiency syndrome
ALA	5-Aminolevulinic acid
AMP	Adenosine 5′-monophosphate
ANF	Atrial natriuretic factor
ANP	Atrial natriuretic peptide (= ANF)
ATP	Adenosine 5′-triphosphate
AVP	Arginine vasopressin
b	Base
bp	Base pair
BPG	2,3-Bisphosphoglycerate
cAMP	3′,5′-Cyclic AMP
CAP	Catabolite activator protein
CDK	Cyclin-dependent protein kinase (in cell cycle)
cDNA	Complementary DNA
CDP	Cytidine 5′-diphosphate
cGMP	3′,5′-Cyclic GMP
CIA	Chemoluminescence immunoassay
CMP	Cytidine 5′-monophosphate
CoA	Coenzyme A
CoQ	Coenzyme Q (ubiquinone)
CSF	colony-stimulating factor
CTP	Cytidine 5′-triphosphate
d	Deoxy-
Da	Dalton (atomic mass unit)
DAG	Diacylglycerol
dd	Dideoxy-
DH	Dehydrogenase
DNA	Deoxyribonucleic acid
dsDNA	Double-stranded DNA
EA	Ethanolamine
EIA	Enzyme-linked immunoassay
ER	Endoplasmic reticulum
FAD	Flavin adenine dinucleotide
Fd	Ferredoxin
FFA	Free fatty acid
fMet	*N*-formylmethionine
FMN	Flavin mononucleotide
Fp	Flavoprotein (containing FMN or FAD)
GABA	γ-Aminobutyric acid
GDP	Guanosine 5′-diphosphate
Glut	Glucose transporter
GMP	Guanosine 5′-monophosphate
GSH	Reduced glutathione
GSSG	Oxidized glutathione
GTP	Guanosine 5′-triphosphate
h	hour
HAT medium	Medium containing hypoxanthine, aminopterin, and thymidine
Hb	Hemoglobin
HDL	High-density lipoprotein
HIV	Human immunodeficiency virus
HLA	Human leukocyte-associated antigen
HMG-CoA	3-Hydroxy-3-methylglutaryl-CoA
HMP	Hexose monophosphate pathway
hnRNA	Heterogeneous nuclear ribonucleic acid
HPLC	High-performance liquid chromatography
hsp	Heat-shock protein
IDL	Intermediate-density lipoprotein
IF	Intermediary filament
IFN	Interferon
Ig	Immunoglobulin
IL	Interleukin
$InsP_3$	Inositol 1,4,5-trisphosphate
IPTG	Isopropylthiogalactoside
IRS	Insulin-receptor substrate
kDa	Kilodalton (10^3 atomic mass units)
K_m	Michaelis constant

LDH	Lactate dehydrogenase
LDL	Low-density lipoprotein
M	Molarity (mol L^{-1})
Mab	Monoclonal antibody
MAP kinase	Mitogen-activated protein kinase
MHC	Major histocompatability complex
MPF	Maturation-promoting factor
mRNA	Messenger ribonucleic acid
N	Nucleotide with any base
NAD^+	Oxidized nicotinamide adenine dinucleotide
NADH	Reduced nicotinamide adenine dinucleotide
$NADP^+$	Oxidized nicotinamide adenine dinucleotide phosphate
NADPH	Reduced nicotinamide adenine dinucleotide phosphate
NeuAc	*N*-acetylneuraminic acid
nm	Nanometer (10^{-9} m)
ODH	2-Oxoglutarate dehydrogenase
PAGE	Polyacrylamide gel electrophoresis
Pan	Pantetheine
PAPS	Phosphoadenosine phosphosulfate
PCR	Polymerase chain reaction
PDH	Pyruvate dehydrogenase
PEG	Polyethylene glycol
PEP	Phosphoenolpyruvate
pH	pH value
P_i	Inorganic phosphate
PK	Protein kinase
PLP	Pyridoxal phosphate
PP	Protein phosphatase
PPP	Pentose phosphate pathway
PQ	Plastoquinone
PRPP	5-Phosphoribosyl 1-diphosphate
PS	Photosystem
PTH	Parathyroid hormone
Q	Oxidized coenzyme Q (ubiquinone)
QH_2	Reduced coenzyme Q (ubiquinol)
R	Gas constant
rER	Rough endoplasmic reticulum
RES	Reticuloendothelial system
RFLP	Restriction fragment length polymorphism
RIA	Radioimmunoassay
RNA	Ribonucleic acid
ROS	Reactive oxygen species
RP	Reversed phase (of silica gel)
rRNA	Ribosomal ribonucleic acid
S	Svedberg (unit of sedimentation coef cient)
SAH	*S*-adenosyl L-homocysteine
SAM	*S*-adenosyl L-methionine
SDS	Sodium dodecylsulfate
sER	Smooth endoplasmic reticulum
sn	Stereospecific numbering
snRNA	Small nuclear ribonucleic acid
SR	Sarcoplasmic reticulum
ssDNA	Single-stranded DNA
TBG	Thyroxine-binding globulin
THB	Tetrahydrobiopterin
THF	Tetrahydrofolate
TLC	Thin-layer chromatography
TPP	Thiamine diphosphate
TRH	Thyrotropin-releasing hormone (thyroliberin)
Tris	Tris(hydroxymethyl)aminomethane
tRNA	Transfer ribonucleic acid
TSH	Thyroid-stimulating hormone (thyrotropin)
UDP	Uridine 5′-diphosphate
UMP	Uridine 5′-monophosphate
UTP	Uridine 5′-triphosphate
UV	Ultraviolet radiation
V_{max}, V	Maximal velocity (of an enzyme)
VLDL	Very-low-density lipoprotein

Quantities and units

1. SI base units

Quantity	SI unit	Symbol	Remarks
Length	Meter	m	1 yard (yd) = 0.9144 m 1 inch (in) = 0.0254 m 1 Å = 10^{-10} m = 0.1 nm
Mass	Kilogram	kg	1 pound (lb) = 0.4536 kg
Time	Second	s	
Current strength	Ampere	A	
Temperature	Kelvin	K	°C (degree Celsius) = K – 273.2 Fahrenheit: °C = 5/9 (°F – 32)
Light	Candela	Cd	
Amount of substance	Mol	mol	

2 Derived units

Quantity	Unit	Symbol	Derivation	Remarks
Frequency	Hertz	Hz	s^{-1}	
Volume	Liter	L	10^{-3} m^3	1 U.S. gallon (gal) = 3.785 L
Force	Newton	N	kg m s^{-2}	
Pressure	Pascal	Pa	N m^{-2}	1 bar = 10^5 Pa 1 mmHg = 133.3 Pa
Energy, work, heat	Joule	J	N m	1 calorie (cal) = 4.1868 J
Power	Watt	W	J s^{-1}	
Electrical charge	Coulomb	C	A s	
Voltage	Volt	V	W A^{-1}	
Concentration	Molarity	M	mol L^{-1}	
Molecular mass	Dalton	Da	1.6605 10^{-24} g	
Molar mass	–	–	g	
Molecular weight	–	M_r	–	Nondimensional
Reaction rate		v	mol s^{-1}	
Catalytic activity	Katal	kat	mol s^{-1}	1 unit (U) = 1.67 10^{-8} kat
Specific activity	–	–	kat (kg enzyme)$^{-1}$	Usually: U (mg enzyme)$^{-1}$
Sedimentation coef cient	Svedberg	S	10^{-13} s	
Radioactivity	Becquerel	Bq	Decays s^{-1}	1 curie (Ci) = 3.7 10^{10} Bq

3 Multiples and fractions

Factor	Prefix	Sym-bol	Example
10^9	Giga	G	GHz = 10^9 hertz
10^6	Mega	M	MPa = 10^6 pascal
10^3	Kilo	k	kJ = 10^3 joule
10^{-3}	Milli	m	mM = 10–3 mol L^{-1}
10^{-6}	Micro	µ	µV = 10^{-6} volt
10^{-9}	Nano	n	nkat = 10^{-9} katal
10^{-12}	Pico	p	pm = 10^{-12} meter

4 Important constants

General gas constant, R	R = 8.314 J mol^{-1} K^{-1}
Loschmidt (Avogadro) number, N (number of particles per mol)	N = 6.0225 10^{23}
Faraday constant F	F = 96480 C mol^{-1}

Further reading

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207	C	Stryer L. Biochemistry. New York: Freeman, 1988, p. 945, Fig. 36–47
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Numbers in *italics* indicate figures.

C

E

G

I

J

K

L

P

Q

R

S

T

U